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AMERICAN GEOPHYSICAL UNION

TRANSACTIONS OF 1944

PART I

REPORTS AND PAPERS

JOINT REGIONAL MEETING
SECTION OF HYDROLOGY
(SOUTH PACIFIC AREA)
WESTERN SNOW-CONFERENCE
AMERICAN SOCIETY OF
AGRICULTURAL ENGINEERS
(PACIFIC COAST SECTION)
BERKELEY, CALIFORNIA
FEBRUARY 17-18, 1944

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TRANSACTIONS OF 1944

GENERAL CONTENTS

Part I--Joint regional meeting, Section of Hydrology (South Pacific Area), Western Snow-Conference, and American Society of Agricultural Engineers (Pacific Coast Section), Berkeley, California, February 17 and 18, 1944

Parts II - VI--Transactions, twenty-fifth annual meeting, June 1 and 2, 1944

PREFACE

The American Geophysical Union was established in 1919 as the American Committee of the International Union of Geodesy and Geophysics, and its Executive Committee on Geophysics of the National Research Council. The objects of the Union are to promote the study of problems concerned with the figure and physics of the Earth, to initiate and coordinate researches which depend upon international and national cooperation, and to provide for their scientific discussion and publication. In the accomplishment of these objects, the Union is divided into Sections following the plan of organization of the International Union of Geodesy and Geophysics. There are now eight Sections, namely, (a) Geodesy, (b) Seismology, (c) Meteorology, (d) Terrestrial Magnetism and Electricity, (e) Oceanography, (f) Volcanology, (g) Hydrology, and (h) Tectonophysics. A Section of Geophysical Chemistry was discontinued May 31, 1924, as the International Union had failed to provide such a Section. The Section of Hydrology was established November 15, 1930--matters pertaining to scientific hydrology referred to the American Geophysical Union had been previously looked after by special committees on Hydrology. The Section of Tectonophysics was established April 9, 1940, for the purpose of promoting and encouraging research of fundamental importance to our knowledge of Earth-structure not covered in any one of the other Sections of the Union.

General assemblies of the Union and meetings of its Sections for presentation and discussion of papers and symposia are held in Washington, D. C., each year. The first annual meetings were those of 1920. Following the formation of the Section of Hydrology, Regional Meetings have been held, usually in joint sessions with other organizations having coordinated interests. For the purpose of such meetings, the Executive Committee of the Section of Hydrology designated selected Regional Areas and their territories, namely: North Continental Divide--Montana, Idaho, eastern Washington, Oregon, and Alberta (affiliated); South Continental Divide--Colorado, Wyoming, Utah, and New Mexico; North Pacific Coast--western Washington, Oregon, Alaska, and British Columbia (affiliated); South Pacific Coast--California, Nevada, Arizona, and Hawaii. Besides the Regional Meetings sponsored by the Section of Hydrology, the Union has also encouraged joint meetings with organizations and societies interested in the discussion of various aspects of the geophysical sciences.

Through 1943, 15 Regional Meetings have been held. The present volume, Part I of the Transactions of 1944, contains the papers of the Joint Regional Meeting of the Section of Hydrology of the American Geophysical Union with the Western Snow-Conference at Berkeley, California, February 18, 19, 1944. The details of the meeting at Berkeley were under the general charge of F. J. VEIHMEYER as Chairman of the South Pacific Coast Area of the Section of Hydrology of the Union and of FRED PAGET as Chairman of the Pacific Coast Area of the Western Snow-Conference. The members of the two Committees for this Regional Meeting were:

South Pacific Area, Section of Hydrology			Western Snow-Conference
H. F. Blaney	M. R. Huberty	H. C. Schwalen	H. P. Boardman
J. E. Church	J. W. Johnson	Fred C. Scobey	James E. Jones
Harold Conkling	Charles J. Kraebel	Franklin Thomas	J. Kittredge
Harry C. Dukes	Charles H. Lee	F. J. Veihmeyer	W. A. Lang
C. C. Elder	Samuel B. Morris	H. A. Wadsworth	Fred Paget
S. T. Harding	M. P. O'Brien	Baldwin M. Woods	

Chairman Veihmeyer reported on the Regional Meeting as follows:

"This Regional Meeting of the South Pacific Area of the Section of Hydrology is the first in two years and the second held at Berkeley. The members of the South Pacific Regional Committee voted to dispense with the proposed meeting in 1943 because of the plea by Federal agencies to restrict the use of transportation facilities and perhaps because of the unwillingness to take the time to attend meetings in view of the seriousness of the task facing the peoples of the country at the time. Whether the improved outlook for an early termination of the war or the desire to keep the interest in our Regional Meetings alive was the deciding motive is not known. The vote for holding a meeting was in the affirmative by a very large majority. It was decided to hold only a one-day session instead of the two-day session as usual in the past.

"The program was planned to include papers dealing with the subject 'The hydrologic basis for post-war planning for Public Works Projects for the conservation and control of water', and it was expected to secure papers from the various Federal and State agencies concerned with hydrologic investigations. This purpose was not entirely accomplished as the titles of the papers published in these Transactions indicate. This was due, perhaps, to the pressure of work in connection with the war and the difficulty in securing transportation which resulted in failure to secure

representation on the program from all of the agencies. The papers presented, however, dealt with important phases of hydrologic investigations, and were well received and occasioned considerable interest and discussion. It is certain that the meeting served the purpose of continuing interest in the subject of hydrology and in the continuation of such sectional programs.

"There were 78 persons registered as in attendance with a number of others who did not sign the registration-cards. There were several from States other than California and various parts of the latter were represented. It may be said truly that meetings which deal with problems of water-utilization and its control always are well attended and create much interest in the West where water is such a valued asset.

"The crowded condition on the Campus of the University, because of the training program for the armed forces, prevented the use of the Campus for the meeting. The place and other facilities for the meeting were provided by the Farm Credit Administration.

"The Western Snow-Conference as usual arranged their program to follow the meeting of the Section. This year, the American Society of Agricultural Engineers arranged their program for the day preceding the meeting of the Section."

The general officers of the American Geophysical Union for the meetings reported upon in this volume were: President, W. C. LOWDERMILK; Vice-President, L. H. ADAMS; General Secretary, J. A. FLEMING. Those for the Section of Hydrology of the Union were: President, J. E. CHURCH; Vice-President, L. G. STRAUB; Secretary, K. H. BEIJ.

The costs of publication for the transactions of the Regional Meeting contained in the present volume were provided by the American Geophysical Union. Assembly and effective editing of the manuscripts were made by F. J. VEIHMEYER and FRED PAGET. The final editing and preparation of master-copy for publication were done by J. A. FLEMING and J. J. CAPELLO of the American Geophysical Union. We are indebted to W. C. HENDRIX and to J. W. GREEN for the necessary redrawing and photographic work for publication. As in past years, the final master-copy was planographed by the Kirby Lithographic Company of Washington.

J. A. FLEMING, General Secretary,
American Geophysical Union

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REPORTS AND PAPERS

REGIONAL MEETING, SOUTH PACIFIC AREA

SECTION OF HYDROLOGY

INTRODUCTION

The meeting was opened by Professor M. P. O'BRIEN who was chairman of the morning session. Professor O'Brien called upon Dr. J. E. CHURCH, President of the Section of Hydrology, who addressed the meeting as follows:

PRESIDENT'S GREETING

I am more than pleased this morning to see the number who have come together, for this meeting was advertised as a local meeting because of the difficulty of transportation and the request that we do not travel if it can be avoided. However, the immediate importance of the work of the American Geophysical Union has impelled us to maintain regional meetings, which could bring the Union to the membership.

Dr. Fleming, our General Secretary, who represents the spirit and energy of the Union, has successfully maintained the annual meeting at Washington and has felt deep satisfaction at the continuance of the regional meetings of the Section of Hydrology and the Snow-Conferences. The last annual meeting at Washington had a total registered attendance of 475 and our Western meetings in Hydrology and Snow have reached nearly half this size.

There are two large things that Dr. Fleming has very close to his heart. One is a membership so large that its size will carry us on to even greater achievements in geophysics. On October 15 there was a membership of 2,075. He even dreams of 2,000 more. We are therefore doing everything we can to meet his optimism.

The mutual interest of our Canadian colleagues in the north in snow- and water-supplies and of our Latin colleagues to the south in ground-water and sanitation has led the Union, quite contrary to the national origins of the international parent body, to grant associate membership to co-workers in other countries. This solidarity of sympathy will add still further to our momentum.

Dr. Fleming's second ambition is a Special Fund of $30,000 to secure for the next three years secretarial assistance and editorship for the Transactions. At the end of this period it is hoped that the membership dues that should be expanded to $5.00 will be sufficient to maintain the income.

The Special Fund long planned has now been given fresh impetus. Dr. Fleming has saved a little over $3,000 in the conduct of the Union and gifts of $3,054 have been reported January 8. He hopes for a total of $10,000. The leaflet "Why the American Geophysical Union needs $5,000 or more" is cogent. [Note: The Special Fund with $10,000 from the Union and its Members and friends and a grant of $20,000 ($6,667 per year for three years) from the Rockefeller Foundation was completed in June 1944. The grant by the Rockefeller Foundation affords evidence, in the judgment of the officers and trustees of that Foundation, of the potentialities of geophysics nationally and internationally.]

In the membership drive that is basic to the endowment and continuing support of the Union, Waldo E. Smith, representing the Section of Hydrology on the Committee on Membership, has prepared a map showing the number of Union Members per million population. Washington, D. C., has a figure of 568.5 and California 35.9. Nevada, the cradle of snow-surveying, has 163.3, an anomaly in the land of cowboys. As a result of 700 letters sent out by him, 113 new memberships have been obtained. The blind spots on the map are the areas of opportunity. Large meetings have already been held in the Central States and the energy of Merrill Bernard is bringing the organization of the Southeastern Area to realization.

In the praise of donors, there is a note of disappointment toward ourselves, which we can readily remove. Secretary Fleming writes "The proportion of 451 contributors from 2,100 members of the Union is surprisingly good" but Chairman Hoyt feels "in some respects disappointed in the showing. For example, in the East in one State with 23 members of the Section only one contributed and in a group of States with 30 members, there were only four contributors. Cali-

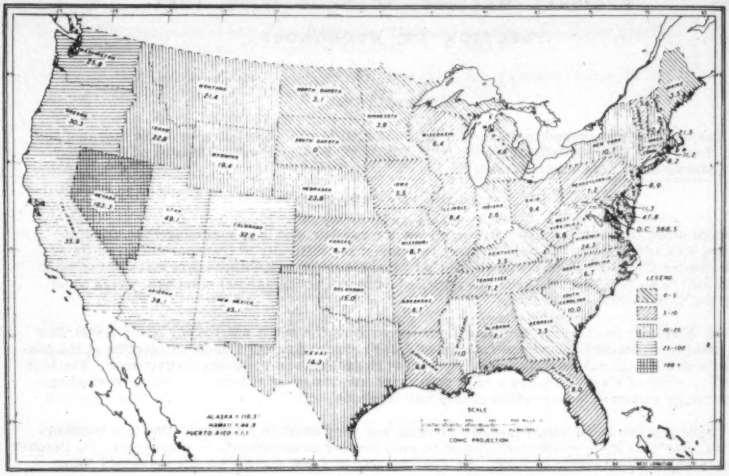

Fig. 1--Members of the American Geophysical Union per million population in the United States, October 15, 1943

fornia as a whole did fairly well but not as well as would be expected considering the number of sectional meetings held." (This challenge has been met by the Western Snow-Conference that has voted a contribution of $100 to the "Fleming Foundation Fund." Can this not be equalled by other groups whose interest in science should be translated into more tangible evidence?)

It is with real regret that I learned recently that a friend and colleague, PAUL L. BEAN, of Lewiston, Maine, had passed away. He firmly established snow-surveying in the Androscoggin Basin of Maine and New Hampshire, where the idea was first born in America, and on its showing he boldly warned the public of the disastrous flood of 1935, an event which he experienced only in late life but his son was privileged to witness in young manhood. The message of his death to me was brief but stirred memories deeply. I desire to share them with you.

Only two weeks earlier I received the following message, dated January 19, 1944, of vision and enthusiasm: "I have your New Year's Greetings of cheer and hope, to which I can subscribe 100 per cent. I can truthfully say that I never conceived of so many things worth while which needed to be done and never felt more like doing the work."

Then on Tuesday, February 8, 1944, came the laconic message from MARY C. KEARNS, his Secretary: "This is to advise you, or perhaps you have already heard, that our Mr. Bean passed away on January 29 from a heart attack. We thought you might be interested in our sad news."

In reply I wrote Miss Kearns as follows:

"Your letter of February 8 is most deeply appreciated for I have always rated Paul Bean among my sturdiest and most aggressive colleagues. His last letter to me was filled with the zest of living and aiding in bringing the world back to peace and progress again. His death does not seem real but I am aware that things can suddenly happen for I myself am now just recovering from a broken vertebra, received at the height of my strength, through sudden accident.

"At the coming annual meeting of the American Geophysical Union, I wish to present a memorial tribute to him as one of the earlier pioneers in snow-surveying in the region in which snow-surveying itself first started in America but where the people were still slow to believe. Can you not send me considerable detail regarding his earlier work as a teacher at the University of Maine

and later as a consulting engineer? The two days spent with him in 1939 gave me a view of his spirit and his day-by-day thinking. I want to round it out into a fuller picture."

I cannot forget his last words to me written in the fullness of his strength, "so many things worth while which need to be done." Can you not take up his torch?

BASIN-STORAGE METHOD OF DEVELOPING FLOOD-HYDROGRAPHS FROM PRECIPITATION-RECORDS

Walter J. Parsons, Jr.

(1) General--The flood-hydrograph at a given point in a river-channel (hereinafter called the point of measurement) is the outflow that results when the basin-inflow (precipitation and snow-melt) has been modified by the complex storage- and loss-characteristics of a river-basin. The development of flood-hydrographs from such basin-inflow data therefore requires the use of some method that will take into account the integrated effect of these various basin-characteristics. In the basin-storage method of developing flood-hydrographs from basin-inflow data, use is made of separate flow-storage relations for each of the various elements of the basin-storage, and separate loss-relations for each of the various elements of basin-loss.

(2) Although there is no clear line of demarcation between the various elements of basin-storage and between the various elements of basin-loss, these may be separated, for purposes of analysis, into relatively simple fractions which tend to act separately. The storage-fractions are: Snow-storage (storage within and under a snow-pack); surface-storage (which includes channel or waterway storage); subsurface storage (in surface-layers of soil above main water-table); and ground-water storage. The loss-fractions are: Evapo-transpiration losses; and deep-seepage losses (outflow from the basin through subterranean channels).

(3) The inflow (rainfall and snow-melt) is first modified by passing through the snow-storage. The resultant flow, hereinafter called equivalent basin mean inflow, is separated at the ground-surface into two fractions, one of which goes into surface-storage and the other into subsurface-storage. The surface-fraction of flow is modified by passing through the surface-storage before reaching the point of measurement in the stream-channel. The fraction of flow which enters the ground is modified by passing through the subsurface-storage. The outflow from subsurface-storage is separated into three fractions: Evapo-transpiration losses; flow to ground-water; and outflow into stream-channels through shallow subsurface-paths. The evapo-transpiration and flow to ground-water fractions are believed to be relatively constant as long as there is free water in the subsurface-storage. These two fractions can therefore be combined into a single unsegregated quantity, none of which contributes to immediate flood-runoff. The flow to ground-water is further modified by passing through ground-water storage and by losses through deep subterranean channels, to produce the relatively steady ground-water outflow.

(4) Thus, the total flow at the point of measurement is considered to come from three sources: Outflow from surface-storage; outflow from subsurface-storage; and outflow from ground-water storage. Under favorable conditions, an observed hydrograph can be divided into these three fractions and the characteristics of the storage that modified each fraction can be determined by analysis. The following method of making this division and determination has been found useful.

(5) Division of total flood-hydrograph into fractions--The observed flood-hydrograph at the point of measurement is plotted on semilog paper using the uniform scale for the time-element (see Fig. 1). The portion of the hydrograph five to ten days after the cessation of rainfall approximates a straight line with a very flat downward slope. This portion of the hydrograph is considered to be entirely outflow from ground-storage and the slope of the line is accepted as characteristic of outflow from ground-water storage. This straight line is extended backward under the flood-peak and connected by a flat S-curve with the relatively uniform flow from ground-water before the flood-peak. The flow below this line is considered to belong entirely to the ground-water fraction of the total flow. This flow is subtracted from the total flow and the remainder replotted. The recession-portion of this residual hydrograph is generally concave upward but the later portion approximates a straight line with a moderate downward slope. This straight portion is considered to be entirely outflow from subsurface-storage and the slope of the line is accepted as characteristic of outflow from subsurface-storage. This straight line is extended backwards under the peak of the hydrograph and connected by an S-curve with the estimated point of beginning of subsurface-flow. The flow below this line is considered to be the subsurface-fraction of the total flow. This flow is subtracted from the previous remainder and the final remainder (surface-fraction)

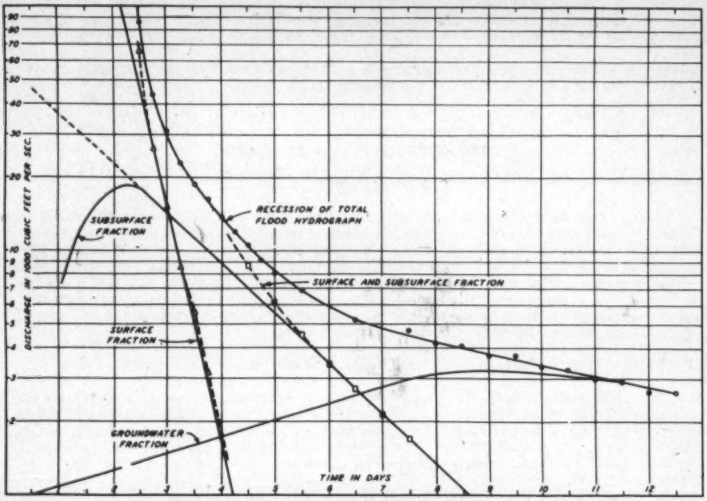

Fig. 1--Graphical recession-analysis, American River at Fair Oaks

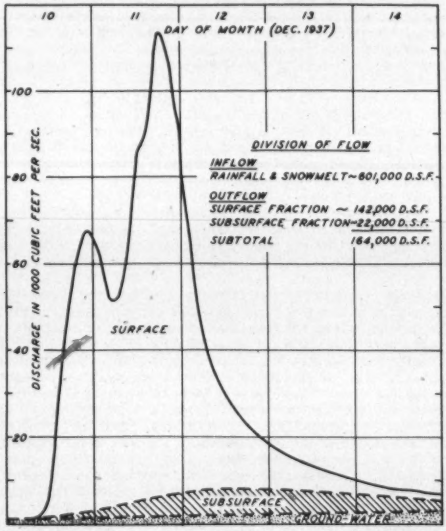

Fig. 2--Division of flood-hydrograph, American River at Fair Oaks

Table 1--Computation of surface flow-storage relation, flood of December, 1937, American River at Fair Oaks

Date	Analysis of flow and storage				Flow-storage relation for 9-hour lag[a]	
	Time	Outflow	Implied storage		Storage	Flow
1937	h	cfs	dsf/4	dsf/4	dsf/4	cfs
				0		
Dec. 15	18	11	11			
				11	11	
	12	20	20			
				31	31	11
	06	34	34			
				65	65	20
14	24	60	60			
				125	125	34
	18	105	105			
				230	230	60
	12	182	182			
				412	412	105
	06	317	317			
				729	729	182
13	24	545	545			
				1,274	1,274	317
	18	950	950			
				2,224	2,224	545
	12	1,680	1,680			
				3,904	3,904	950
	06	2,950	2,950			
				6,854	6,854	1,680
12	24	5,100	5,100			
				11,954	11,954	2,950
	18	8,800	8,800			
				20,754	20,754	5,100
	12	15,300	15,300			
				36,054	36,054	8,800
	06	26,500	26,500			
				62,554	62,554	15,300
11	24	46,300	46,300			
				108,854	108,854	26,500
	18	79,000	79,000			
				187,854	187,854	46,300
	12					

[a]The time-scale does not apply to these columns.

replotted. The recession-portion of this curve becomes a straight line shortly after the cessation of inflow (rainfall and snow-melt) and the slope of this line is accepted as characteristic of outflow from surface-storage. A sample division of a flood-hydrograph into these fractions is shown on Figure 2.

(6) Having determined the amount of each fraction of the total runoff, and knowing the equivalent basin mean inflow (rain and snow-melt as modified by snow-storage), an evaluation can be made of the average surface-infiltration rate and of the unsegregated average rate of loss from subsurface-storage. By determination of these average rates in various floods, the maximum values that could exist and the variation of these rates during the duration of a storm can be closely estimated.

(7) Development of basin-flow versus storage-relations--Flow-storage curves for the surface- and subsurface-fractions of basin-storage were developed by integrating the straight-line recessions obtained in the manner described in the preceding paragraph. In these integrations, lag-type curves were developed rather than reservoir-type curves since the former type has been found to better represent the flow-storage relationship that exists in the various stream-basins of the Sierra Nevada. (The basic assumption of the lag-type curve is that a specific amount of storage will cause

a specific outflow a fixed interval of time after the occurrence of the storage.) In the integration-process, the interval or lag-time used is that which produces the best reproduction of observed flood-hydrographs. Hence the determination of lag-time is an empirical process. The lag-time for the subsurface-relation has usually been found to be from 6 to 12 hours longer than the lag-time for the surface-relation. A sample graphical recession-analysis and a sample integration of recession-data into a flow-storage relation for the surface-storage fraction are shown on Figures 1 and 2 and Table 1.

Table 2--Sample calculation, flood-hydrograph of December, 1937, American River at Fair Oaks

Day and period	Inflow: Equivalent basin mean inflow[a]		Inflow: Maximum surface infiltration[b]		Fraction to: Surface storage	Fraction to: Subsurface-storage	Outflow from: Subsurface - storage: Gross[c]	Outflow from: Subsurface - storage: To groundwater, etc.	Outflow from: Subsurface - storage: To stream	Outflow from: Surface storage[d]	Outflow from: Groundwater storage[e]	Total
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(14)
	in	*	in	*	*	*	*	*	*	*	*	*
Dec. 9, 1	0.00	0			0	0	0	0	0	0	1	1
2	0.00	0			0	0	0	0	0	0	1	1
3	0.64	131			0	131	66	66	0	0	1	1
4	1.79	367	0.27	332	35	332	66	66	0	0	1	1
10, 1	1.81	371	0.22	271	100	271	67	66	1	0	1	2
2	1.55	318	0.18	221	97	221	67	66	1	9	1	11
3	0.36	74	0.17	209	0	74	68	66	2	33	1	36
4	1.17	240	0.16	197	43	197	68	66	2	55	1	58
11, 1	1.90	390	0.15	185	205	185	69	66	3	47	1	51
2	1.34	275	0.15	185	90	185	69	66	3	44	1	48
3	0.52	106	0.15	185	0	106	70	66	4	83	1	88
4	0.36	74	0.15	185	0	74	71	66	5	96	1	102
12, 1	0.28	57	0.15	185	0	57	72	66	6	74	1	81
2	....	...	....	...	...	...	72	66	6	50	1	57
3	....	...	....	...	...	...	72	66	6	32	2	40
4	....	...	....	...	...	...	72	66	6	19	2	27
13, 1	....	...	....	...	...	...	71	66	5	11	2	18
2	....	...	....	...	...	...	70	66	4	7	2	13
3	....	...	....	...	...	...	70	66	4	4	2	10
4	....	...	....	...	...	...	70	66	4	2	2	8
14, 1	....	...	....	...	...	...	70	66	4	1	2	7
2	....	...	....	...	...	...	69	66	3	1	2	6
3	....	...	....	...	...	...	69	66	3	1	2	6
4	....	...	....	...	...	...	68	66	2	0	2	4

[a] Basin mean rainfall modified by any influence of snow-melt and snow-storage.
[b] Basin mean maximum infiltration that is possible under conditions current at the moment.
[c] Routed from Column (7) by subsurface flow-storage relation using 15-hour lag.
[d] Routed from Column (6) by surface flow-storage relation using 9-hour lag.
[e] Estimated from general conditions.
* In 1000 (dsf/4).

(8) Method of developing a flood-hydrograph from precipitation-data--The equivalent basin mean inflow is calculated by reducing the basin mean precipitation by the quantity which fell as snow, adding the quantity of concurrent snow-melt and modifying the resultant quantity by routing it through snow-storage. This portion of the procedure is more fully described in the companion paper by Joseph B. Paulson, Jr., entitled "A method for calculating the effect of snow on runoff during rainstorms." The basin mean inflow, so computed, is the equivalent of a rainstorm falling on a snow-free basin and can be treated as such. (When the basin is actually snow-free and all precipitation is rain, the equivalent basin mean inflow is equal to the basin mean precipitation.) The equivalent basin mean inflow is then separated by means of an estimated variable basin mean-surface infiltration-factor into a fraction that passes only through surface-storage and a remainder that passes through subsurface-storage. The surface-fraction is routed through the surface-storage by means of the surface flow-storage relation. The subsurface-fraction is similarly routed using the subsurface flow-storage relation. The resulting gross outflow from subsurface-storage is then separated by means of a constant subsurface loss-factor into (1) a flow that reaches the point of measurement through subsurface-channels and (2) an unsegregated fraction that supplies

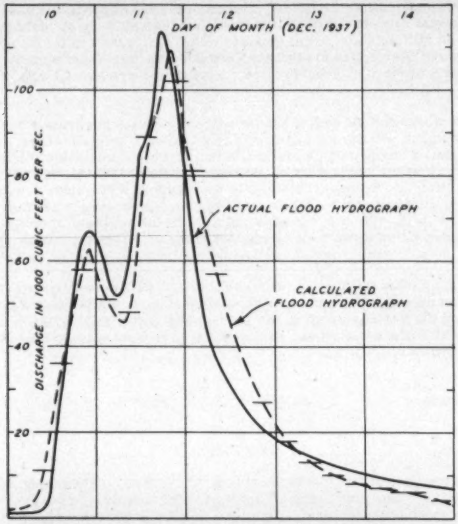

Fig. 3--Observed and calculated hydrographs, flood of December 1937, American River at Fair Oaks

flow to ground-water and evapo-transpiration losses. The latter fraction is assumed to remain constant throughout the flood-period and persists as long as there is any water in subsurface-storage. The outflow from ground-water storage is usually relatively small in proportion to the flow from other sources and it has been found unnecessary to determine its value by a routing procedure. In lieu thereof, the outflow from ground-water is roughly estimated by independent means. The outflows from surface, subsurface, and ground-water storage are then added directly to obtain the total flow in the stream-channel at the point of measurement.

(9) The computational procedure is illustrated by Table 2. Column (2) is the equivalent basin mean inflow, that is, the basin mean rainfall modified by any influence of snow-melt and snow-storage. Column (4) is the estimated maximum potential surface-infiltration during each quarter-day period. Columns (6) and (7) are the separation of the inflow into the fraction going into surface-storage and the fraction entering subsurface-storage. Column (8) is the gross outflow through all channels from subsurface storage obtained by routing Column (7) through subsurface storage by means of the subsurface flow-storage relation. Columns (9) and (10) are the separation of this gross outflow into the fraction going to ground-water and to supply evapo-transpiration losses, and the fraction that reaches the stream-channel. Column (11) is the outflow from surface-storage obtained from Column (6) by a routing procedure using the surface flow-storage relation. Column (12) is the outflow from ground-water storage obtained by a rough estimation based on general conditions. Column (13) is the total outflow from all sources and is the sum of columns (10), (11), and (12). The resultant calculated hydrograph is shown on Figure 3 where it is compared with the observed hydrograph of the same flood.

(10) Conclusions--The basin-storage method provides a flexible means of estimating the flood-hydrograph that would result from extremely severe storms such as the estimated worst possible storm. It is believed to be superior to the unit-hydrograph method when basin-conditions are such that the ratio between initial quantities in surface, subsurface, and ground-water storages is highly variable so that the total initial storage in various floods is composed of varying amounts of the three fractions. This condition is indicated when observed flood-hydrographs from apparently

similar storms have radically different shape. The method also permits the use of data from more observed hydrographs than the unit-hydrographic method since basic data can be derived from complex as well as simple short-term storms. Simple storms and floods are relatively rare in the territory west of the Sierra Nevada and the Cascade Mountains and usually do not adequately cover the range of damaging floods. Furthermore, damaging floods are usually of the complex type.

(11) The weakness of the method lies in its inability to develop accurately the rising limb of the various storage-relations and the necessity of using the well-defined falling limb for both rising and falling conditions. The use of this method is therefore not advisable for small or medium-sized floods which usually occur under conditions when the rising and falling limbs of the flow-storage relations are different. However, its use is recommended for large floods which almost always occur under conditions where the difference between the two limbs is immaterial. Therefore, the method appears to provide a reasonable solution to the problem of analyzing and reconstituting the large complex flood-flows which occur on many of the river-basins along the West Coast.

(12) Acknowledgments--The writer has utilized theories and procedures previously proposed by numerous investigators in this field, particularly those of B. S. BARNES and R. E. HORTON. Assistance in organizing the various parts of the method has come from OTTO H. MEYER, A. L. BROSIO, and C. E SCHNEIDER who now are or formerly have been employees of the United States Engineer Office at Sacramento, California.

U. S. Engineer Office,
Sacramento, California

DISCUSSION

S. T. HARDING (University of California, Berkeley, California)--This interesting method that Mr. Parsons has reported, I think, has many advantages. For one thing, it breaks down the total flow into three factors: Outflow from surface-storage; outflow from subsurface-storage; and outflow from ground-water storage. The method would not, however, be applicable to some humid areas, due to variations in rain and snow, as it would be for our Sierra streams. The method is logical in breaking the flow into three fractions and he can analyze the major items of surface-storage and not be confronted by the variations in the other two.

EDWIN S. FULLER (Los Angeles County Flood-Control District)--I would like to ask Mr. Parsons how he would determine ground-water flow.

W. J. PARSONS--That portion of the ground-water flow had to be estimated from general information. The ending point and the beginning point are known, and in cases where intermediate points have to be worked out, this can be done closely enough from general information.

EDWIN S. FULLER--We used a similar system in flood-control work in Los Angeles. We found in general that we were apt to select a curve that would straighten out the rest of the curves. Obviously this is an arbitrary method and its use detracts from the value of the procedure. We have, however, 16 reservoirs for which we can work out very accurately inflow-data. The breakdown method was quite successful. However, for one reservoir, the recession-hydrograph refused to straighten itself out on log-paper and gave difficulty in extrapolating. I am working now on a different system.

W. J. PARSONS--That condition that you spoke of may mean the total storage of the basin was connected and did not separate into fractions.

EDWIN S. FULLER--Yes, there was no definite breakdown between the ground-water and the subsurface.

W. J. PARSONS--It is fortunate when they do separate as they have on a half-dozen streams in the Sierras. We acknowledge that your luck can run out.

L. STANDISH HALL (East Bay Municipal Utility District, Oakland, California)--Is the water in the snow-packs included?

W. J. PARSONS--No. Our surface-fraction is the portion of the total runoff which passes through surface-storage. The fraction which passes through subsurface-storage is the subsurface-fraction. Ground-water storage may not actually be below the ground, but may be in the snow-pack. We can only classify the various fractions of runoff by their final results.

L. STANDISH HALL--You do not really try to break them down according to their origins.

W. J. PARSONS--We break them down, for purposes of study, into fractions which have consistent characteristics. The actual origins of the runoff must remain unknown.

J. B. BROWN (Agricultural Extension Service, University of California, Berkeley, California)--As storms continue, the rate of infiltration approaches a constant and, in most cases, this rate is small. Also, the effects of evaporation and transpiration are small during the course of a continuing storm. Hence the principal reduction of flood-peaks is due to channel-storage. The principle of flow-reduction can be stated simply: "A rising river always discharges less water than comes into it." The following is a homely illustration: Turn on the tap in a wash-basin leaving the drain open. Water builds up in the basin. The outflow is less than the inflow by the amount built up in the basin.

In flood-flow studies of Sacramento River system in 1913, a peak-reduction of 10,000 cubic feet per second out of a flow of 180,000 cubic feet per second was calculated for one section of the river-system. Our methods at that time were not as elaborate as those set forth in this paper. The authors are to be commended for their consideration of the many elements which enter into this complex problem.

N. F. MEADOWCROFT (Federal Power Commission, San Francisco, California)--Your example was at one point at Fair Oaks. What method did you have for maximum storage of the whole basin as affecting the infiltration-rates? Did you break it up by areas on the basin?

W. J. PARSONS--The method was entirely empirical. We knew how much came in, the equivalent basin mean inflow. We knew how much went out, the surface-fraction. The remainder must have penetrated through the surface. By dividing the total quantity by the period during which it was passing through the surface, we obtained an average rate for the entire basin above the Fair Oaks Station. That was then stated in terms of inches over the area. In this particular analysis, we had the number of second-foot days that went into different fractions. We knew the length of time during which they must have passed. By repeating that for numerous other fractions, we were able to arrive at rates for hypothetical floods. It was entirely empirical, however. The rates seem reasonable. When they are not, we reexamine our calculations.

A METHOD FOR CALCULATING THE EFFECT OF SNOW ON RUNOFF DURING RAINSTORMS

Joseph B. Paulson, Jr.

(1) General--Most drainage-areas along the Sierra Nevada are covered to some extent with snow when heavy storms occur, which condition complicates the problem of computing the flood-hydrograph. This method was devised and developed by the author in order to supply the basic information of "equivalent rainfall", necessary for the calculation of the flood-hydrograph from rain falling on a basin covered to a known extent with a snow-blanket. Basin-mean increments of "equivalent rainfall" or "equivalent contribution to runoff" are calculated, which may be used in any of the methods for computing the hydrograph. The object of this method is to calculate the increments of rain on the basin when it is free of snow, which would produce the same hydrograph as the rain and snow-melt. The problem involves snow-melt, the storage of rain in the snow, the effect of elevation on the amounts of rain and snow-melt, and the delay in surface-runoff caused by the snow-cover. The method consists of (1) the calculation of the amount of snow-melt that occurs in successive periods in each zone of elevation in the area, (2) the determination from the basin-mean values, of concurrent rainfall for the same zones of elevation, and (3) the calculations of the "equivalent contribution to runoff" for the successive periods from each zone of elevation and from the basin.

(2) Basic factors--In review, the complex, largely unknown effect of snow during warm rains can be roughly described in the following terms. As the snow begins to melt, the initial melt-water is stored in the snow-cover. If warm rain then falls on the snow-mantle, it may also be stored [see 1 of "References" at end of paper]. The water from these sources percolates down-

ward in the snow, most of it filling the pore-space and being held in the lower portion of the snow-structure. As the snow-melt and rain continue the ice-crystal matrix of the snow-structure is melted, decreasing the depth of snow and the possible reservoir space with a resulting increase in the average density of the snow. Discharge of the stored or suspended water begins when the capillary forces are more than balanced by gravity with this discharge continuing as long as this condition exists [2]. Runoff from rain on snow-cover is delayed by the rain having to pass through the crystalline structure and through the reservoir of stored water in the snow. In addition, surface-runoff is delayed by the obstructing effect of the snow-mantle, that is, by snow-dams. With saturated snow, the rain will still be delayed by its passage through the snow. As a result, the rate of contribution to runoff may be greater than the rate of rainfall or greater than the rate of rainfall plus snow-melt because of the release of water stored in the snow due to the melting of the snow. Snow-melt generally decreases as elevation increases due to the drop in temperature, notwithstanding the increase in wind-velocity with elevation. Also the precipitation usually varies with elevation, increasing in amount to a certain elevation and then decreasing above that level. Thus, the contribution to runoff from a drainage-area having an appreciable range of elevation is further complicated. Since precipitation, snow-cover, and snow-melt usually vary consistently with elevation, it is possible in mountainous country to divide the total basin into narrow zones of elevation within which each of the above basic factors can be assumed as constant for short periods. The "equivalent rainfall" or "equivalent contribution to runoff" is then calculated separately for each zone and period.

(3) The method--This complex problem can be simplified by the assumption of no compaction of the snow during melting or from rainfall, and the use of the following factors for each increment of area between 1000-foot contours: (1) An average density of snow-cover at the start of the snow-melt; (2) an average density of the snow-cover when the "equivalent contribution to runoff" begins; and (3) the average density of the snow-cover when no further storage can occur, increased above the true value to provide for the delaying action of the snow-cover on runoff. These values should be varied to suit local or desired conditions, based on data from the field and laboratory. The assumption of no compaction of the snow during melting incurs but slight error as can be seen by examination of the curve showing the depth during ripening of a column of snow, which appeared in "An outline of the thermodynamics of snow-melt" by W. T. Wilson [2]. However, if the average values of the depth of snow during melting are known, these can be used. The method can best be explained by a sample set of calculations for an assumed set of meteorological conditions and snow-cover. In the example cited, the calculations were made to find the worst possible effect of the given rain and snow-cover. Thus, the density-factors in the order listed were assumed to be 15, 70, and 70 per cent, respectively. The method is flexible enough so that these values could be varied by zones or periods. Six-hour periods were used but shorter periods could be used for smaller areas.

(4) Calculation of snow-melt--The following approximate formula, suggested by Phillip Light in his "Analysis of high rates of snow-melting" [3], was used as the basis for the calculations to determine the snow-melt.

$$D = KU\,[0.00184(T-32)\,10^{-0.0000156h} + 0.00578\,(e-6.11)]$$

where D is melt in inches of water per 6-hour period; U is wind-velocity at the 50-foot level in miles per hour; T is temperature at the 10-foot level in °F; e is vapor-pressure at the 10-foot level in millibars; h is elevation above mean sea-level in feet; and K is a regional or basin constant. (K = 0.6 was used in the example.) The assumed water-content and depth of snow-cover as well as the proportion of the area in each elevation zone is shown in Table 1. Having given the water-content of the snow on the ground at the beginning of the snow-melt period and using the dew-point, wind-velocity, and temperature as variables, the snow-melt was calculated in inches of water for each six-hour period on each zone of elevation. Since this part of the calculation is not original and the assumptions involved do not affect the remainder of the method, only the final results are shown in Table 2.

(5) Determination of precipitation--In order to distribute the basin-mean precipitation to the zones of elevation for each six-hour period, an elevation-precipitation curve was constructed using the total storm-precipitation at the stations in or near the area with their respective elevations. This curve was adjusted so that the total precipitation on all the zones of elevation equaled the basin-mean precipitation. The total storm-values for each zone indicated on this curve were then distributed through the periods of the storm proportional to the total basin-mean values. The assumed distribution of basin-mean precipitation in the example is listed in Table 3 starting with the time of beginning of snow-melt.

Table 1--Initial data for snow-cover and area

Elevation of zone	Average initial water-content	Snow-cover depth[a]	Proportion area in zone
ft.	in.	in	
100- 1,000	0.5	3.33	0.144
1,000- 2,000	1.0	6.66	0.048
2,000- 3,000	3.0	20.00	0.129
3,000- 4,000	10.0	66.7	0.121
4,000- 5,000	8.5	56.6	0.138
5,000- 6,000	6.0	40.0	0.152
6,000- 7,000	5.0	33.3	0.133
7,000- 8,000	5.0	33.3	0.089
8,000- 9,000	5.0	33.3	0.039
9,000-10,000	5.0	33.3	0.007

[a] At density 15 per cent.

Table 2--Accumulated snow-melt in inches of water

Elevation of zone	Period ending											
	6	12	18	24	30	36	42	48	54	60	66	72
100- 1,000	0.2	0.5										
1,000- 2,000	0.1	0.5	1.0									
2,000- 3,000		0.2	0.7	1.5	2.6	3.0						
3,000- 4,000		0.1	0.5	1.2	2.2	3.4	5.0	7.0	8.6	9.8	10.0	
4,000- 5,000			0.3	0.8	1.6	2.7	4.2	6.0	7.8	8.5		
5,000- 6,000			0.1	0.5	1.1	2.0	3.3	4.9	6.0			
6,000- 7,000				0.2	0.6	1.3	2.4	3.8	4.9	5.0		
7,000- 8,000				0.1	0.4	0.9	1.8	2.9	3.8	4.3	4.6	4.7[a]
8,000- 9,000					0.1	0.5	1.2	2.1	2.8	3.2	3.3[a]	
9,000-10,000						0.2	0.7	1.4	1.9	2.1[a]		

[a] Temperatures too cold for further snow-melt.

Table 3--Distribution of precipitation

Period in hours	6-hour increment	Period in hours	6-hour increment	Period in hours	6-hour increment
	in		in		in
0 - 6	0.0[a]	30 - 36	2.9	60 - 66	2.2
6 - 12	0.0[a]	36 - 42	2.8	66 - 72	0.6
12 - 18	0.0[a]	42 - 48	0.7	72 - 78	0.4
18 - 24	1.0	48 - 54	2.6	78 - 84	0.3
24 - 30	2.8	54 - 60	4.4	Total	20.7

[a] Less than 0.1 inch in basin.

(6) Calculation of equivalent contribution to runoff--The calculation of the "equivalent contribution to runoff" for each zone was made as follows: (1) The depth of snow at the end of each period was determined by subtracting the snow-melt (in inches of snow) from the initial depth of snow; (2) these values were then multiplied by the density at which "equivalent contribution to runoff" takes place; (3) the accumulated precipitation and snow-melt water at the end of each period was listed; and (4) the "equivalent contribution to runoff" during each period obtained by calculating the excess of accumulated water over the values obtained in the above calculation. The contribution from each zone was then multiplied by the proportion of area in each zone and these values added to obtain the basin-mean contribution for each period. A sample calculation of

Table 4 --Sample calculation of equivalent contribution to runoff and

Line	Elevation zone	Period ending in hours									
		0	6	12	18	24	30	36	42	48	54
	ft.										
1	100- 1,000	3.33	2.0	0.0							
2			1.4	0.0		Snow all melted, therefore contribution to runoff					
3			0.5	0.5[a]							
4			0.0	0.5	0.0	0.4	1.1	1.1	1.1	0.2	1.0
5			0.0	0.072	0.0	0.058	0.158	0.158	0.158	0.029	0.144
1	1,000- 2,000	6.66	6.0	3.3	0.0	.....	.....	.....	.....	.....	.....
2			4.2	2.3	0.0	.....	.....	.....	.....	.....	.....
3			1.0	1.0	1.0	.....	.....	.....	.....	.....	.....
4			.....	0.0	1.0	0.5	1.5	1.6	1.4	0.4	1.4
5			.....	0.0	0.048	0.024	0.072	0.077	0.067	0.019	0.067
1	2,000- 3,000	20.0	20.0	18.7	15.3	10.0	2.7	0.0	.....	.....	.....
2			14.0	13.1	10.7	7.0	1.9	0.0	.....	.....	.....
3			3.0	3.0	3.0	3.8	5.9	8.1	.....	.....	.....
4			.....	.....	.....	0.0	4.0	4.1[b]	2.2	0.5	2.0
5			.....	.....	.....	0.0	0.516	0.529	0.284	0.065	0.258
1	3,000- 4,000	66.7	66.7	66.0	63.3	58.6	52.0	44.0	33.3	20.0	9.3
2			Calculations not necessary				36.4	30.8	23.3	14.0	6.5
3			10.0		Data not necessary			17.1	20.1	20.8	23.5
4			.....	.....	.....	.....	.....	.....	0.0	6.8	10.2[c]
5			.....	.....	.....	.....	.....	.....	0.0	0.823	1.234
1	4,000- 5,000	56.6	56.6	56.6	54.6	51.3	46.0	38.6	28.7	16.6	6.7
2			.....	.....	.....	.....	.....	27.0	20.1	11.6	4.7
3			8.5	8.5	.....	.....	.....	16.8	20.3	21.2	24.4
4			.....	.....	.....	.....	.....	0.0	0.2	9.4	10.1
5			.....	.....	.....	.....	.....	0.0	0.028	1.297	1.394
1	5,000- 6,000	40.0	40.0	40.0	39.3	36.7	32.7	26.7	18.0	7.3	0.0
2			.....	.....	.....	.....	.....	18.7	12.6	5.1	0.0
3			6.0	6.0	.....	.....	.....	14.6	18.3	19.2	22.5
4			.....	.....	.....	.....	.....	0.0	5.7	8.4	8.4
5			.....	.....	.....	.....	.....	0.0	0.866	1.277	1.277
1	6,000- 7,000	33.3	33.3	33.3	33.3	32.0	29.3	24.7	17.3	8.0	0.7
2			.....	.....	.....	.....	.....	17.3	12.1	5.6	0.5
3			5.0	5.0	.....	.....	.....	13.4	17.0	17.9	21.1
4			.....	.....	.....	.....	.....	0.0	4.9	7.4	8.3
5			.....	.....	.....	.....	.....	0.0	0.652	0.984	1.104
1	7,000- 8,000	33.3	33.3	33.3	33.3	32.7	30.7	27.3	21.3	14.0	8.0
2			.....	.....	.....	.....	.....	19.1	14.9	9.8	5.6
3			5.0	5.0	.....	.....	.....	13.1	16.4	17.3	20.4
4			.....	.....	.....	.....	.....	0.0	1.5	6.0	7.3
5			.....	.....	.....	.....	.....	0.0	0.134	0.534	0.650
1	8,000- 9,000	33.3	33.3	33.3	33.3	33.3	32.6	30.0	25.3	19.3	14.7
2			.....	.....	.....	.....	.....	.....	17.7	13.5	10.3
3			5.0	5.0	.....	.....	.....	.....	15.6	16.3	19.2
4			.....	.....	.....	.....	.....	.....	0.0	2.8	6.1
5			.....	.....	.....	.....	.....	.....	0.0	0.109	0.238
1	9,000-10,000	33.3	33.3	33.3	33.3	33.3	33.3	32.0	28.6	24.0	20.6
2			.....	.....	.....	.....	.....	.....	.....	16.8	14.4
3			5.0	5.0	.....	.....	.....	.....	.....	15.1	17.7
4			.....	.....	.....	.....	.....	.....	.....	0.0	3.3
5			.....	.....	.....	.....	.....	.....	.....	0.0	0.023
Basin mean increments using 70%		0.0	0.0	0.072	0.048	0.082	0.746	0.764	2.189	5.137	6.389
							Accumulated total, 25.051 inches				
Basin mean increments using 60%		0.0	0.0	0.072	0.048	0.082	0.785	0.725	3.303	4.899	5.871
							Accumulated total, 25.239 inches				
Rain only		0.0	0.0	0.0	0.0	1.0	2.8	2.9	2.8	0.7	2.6
							Accumulated total, 20.7 inches				
Rain plus snow-melt		0.0	0.034	0.100	0.192	1.354	3.338	3.550	3.656	1.758	3.424
							Accumulated total, 25.729 inches				

60	66	72	78	84
equals increments of rainfall				
1.7	0.9	0.2	0.2	0.1
0.245	0.130	0.029	0.029	0.014
.....	.....	.....	.....	.....
.....	.....	.....	.....	.....
.....	.....	.....	.....	.....
2.3	1.2	0.3	0.2	0.2
0.110	0.058	0.014	0.010	0.010
.....	.....	.....	.....	.....
.....	.....	.....	.....	.....
.....	.....	.....	.....	.....
3.3	1.7	0.5	0.3	0.2
0.426	0.219	0.064	0.039	0.026
1.3	0.0	.....	.....	.....
0.9	0.0	.....	.....	.....
28.2	30.5	.....	.....	.....
10.3[d]	3.2	0.7	0.4	0.3
1.246	0.387	0.085	0.048	0.036
0.0	.....	.....	.....	.....
0.0	.....	.....	.....	.....
29.9	.....	.....	.....	.....
10.2	2.7	0.7	0.5	0.4
1.408	0.373	0.097	0.069	0.055
.....	.....	.....	.....	.....
.....	.....	.....	.....	.....
.....	.....	.....	.....	.....
5.7	2.8	0.8	0.5	0.4
0.866	0.426	0.122	0.076	0.061
0.0	.....	.....	.....	.....
0.0	.....	.....	.....	.....
26.7	.....	.....	.....	.....
6.1	2.8	0.7	0.5	0.4
0.811	0.372	0.093	0.067	0.053
4.7	2.7	2.0	.....	.....
3.3	1.9	1.4	.....	.....
25.7	28.3	29.1	Freezing	
7.6	4.0	1.3	and snow	
0.676	0.356	0.116	.....	.....
12.0	11.3	11.3	.....	.....
8.4	7.9	7.9	.....	.....
24.1	26.6	Freezing and snow		
6.8	3.0	.....	.....	.....
0.265	0.117	.....	.....	.....
19.3	19.3	19.3	.....	.....
13.5	13.5	13.5	.....	.....
22.0		Freezing and snow		
5.2	.....	.....	.....	.....
0.036	.....	.....	.....	.....
6.089	2.438	0.504	0.338	0.255
5.846	2.404	0.611	0.338	0.255
4.4	2.2	0.6	0.4	0.3
4.760	2.255	0.608	0.4	0.3

Notes on Table 4

Line 1 = Average depth of the snow; this quantity is reduced successively in each period by depth of snow melted; original snow-structure assumed to persist with no compaction occurring.

Line 2 = (Depth of snow × density-factor) for "equivalent contribution to runoff" using density-factor = 0.70; line 1 calculations may be omitted and line 2 calculated direct; quantities are a measure of the storage-capacity within the snow and on the ground-surface behind snow-dams.

Line 3 = Accumulated water, that is, original water-content of snow plus accumulated total rainfall. [a]Contributions to runoff start in period in which values in line 3 exceed line 2.

Line 4 = Contribution to runoff (Line 3 - line 2 - sum of previous values in line 4). [b]8.1 - 0.0 - 4.0. [c]23.5 - 6.5 - 6.8. [d]28.2 - 0.9 - 6.8 - 10.2. When snow is all melted, the contribution to runoff equals increment of rainfall.

Line 5 = Contribution from zone = (Line 4 × weighting-factor) that is, proportion of total area in zone shown in Table 1.

"equivalent basin-mean contribution to runoff" from rain and snow-melt is shown in Table 4. Following these calculations in the Table there is a comparison between the "equivalent contribution to runoff" as calculated and the corresponding rain and rain plus snow-melt values. It will be seen that the "equivalent contribution to runoff" differs radically from both of these values. In order to ascertain the effect of lowering the values of the "equivalent contribution to runoff" density-factors, another calculation was made using density of 60 per cent for both values. The increments from this calculation are tabulated immediately below those in the sample. Figure 1 is a graphic comparison of the values in the sample.

(7) Acknowledgments--The writer has utilized theories and procedures for calculating the amount of snow-melt developed by the Hydrometeorological Section of the United States Weather Bureau and has carried these an additional step in calculating the "equivalent rainfall" or "equivalent contribution to runoff", a quantity necessary for the development of runoff-hydrographs. The writer wishes to express his appreciation to W. J. PARSONS, JR., for his advice in the preparation of this paper.

References

[1] MERRILL BERNARD and WALTER F. WILSON, A new technique for the determination of heat necessary to melt snow, Trans. Amer. Geophys. Union, pp. 178-181, 1941.

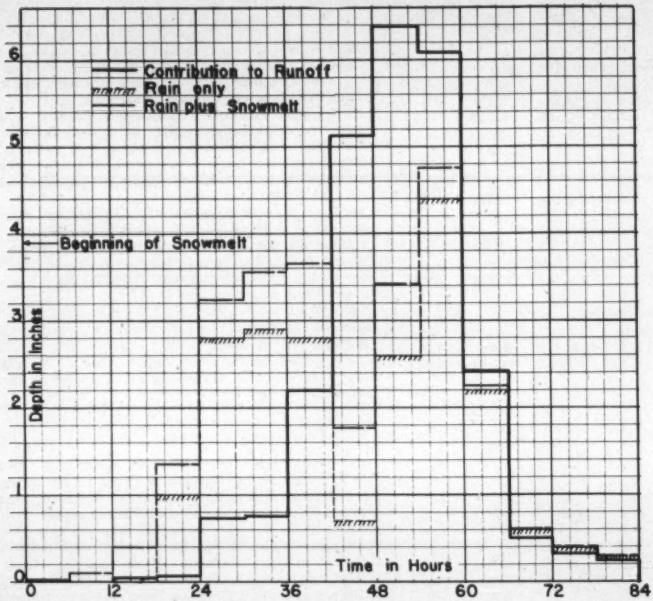

Fig. 1--Comparison of equivalent contribution to runoff with rain and rain plus snow-melt

[2] W. T. WILSON, An outline of the thermodynamics of snow-melt, Trans. Amer. Geophys. Union, pp. 182-195, 1941.
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DISCUSSION

R. K. LINSLEY (U. S Weather Bureau, Sacramento, California)--A paper such as Mr. Paulson has presented is not open to a great deal of discussion. He has outlined a procedure for determining the delaying action of the snow-pack on runoff. It might be called a "routing method" for it is analogous to routing stream-flow through valley-storage.

It is characteristic of most routing procedures that the arithmetic of the computation is direct and without question. The principal problem in routing is the determination of storage. In Mr. Paulson's procedure storage is determined by the snow-density assumed to represent the ultimate water-holding capacity of the snow. The necessary research to determine the proper values of this factor has not yet been performed. When the information is obtained it is quite likely that it will not prove to be a constant but will vary with the physical structure of the snow. In addition it seems probable that because of the relatively low capillarity of snow the control will rest in the lower snow-depths so that as water percolates downward the lower layers will reach the ultimate water-holding capacity and discharge will begin before the entire snow-column reaches the critical density. Such an action might also occur above an ice-crust in the snow-profile without percolation

moving to the ground-surface. The mechanical action of intense rainfall also acts to break down the snow-structure more rapidly than simple melting and thus permits earlier release of the accumulated water.

Once discharge has begun we are faced with another unknown, the delaying action of the snow on runoff. If the lower layer of snow is quite wet it cannot support itself and rests on the ground-surface requiring runoff-water to percolate laterally through the snow or upper soil-layers with a resulting decrease in discharge-rate to a stream. On the other hand, we all have seen snow-bridges over small gullies and depressions in the soil, thus permitting relatively unobstructed surface-runoff. The existence of grass, bushes, or other supporting vegetation on the soil-surface will assist such action.

Beyond these possible effects there is of course the problem of average depth versus actual distribution. The snow-depth is far from uniform, even within a narrow zone of elevation. Drifting and unequal melting in light and shade act to cause a variable pattern. As a result snow disappears in some spots more rapidly than in others. Any computation using average depth will indicate complete disappearance of snow before all of the patches of above average snow have melted.

For each possible complication of the phenomena of snow-melting that I have mentioned there are probably many more unmentioned. This means simply that even after the values of density at the beginning of runoff and at the ultimate water-holding capacity have been determined experimentally, we will not know the true "effective" values for a large natural basin. The final value used will be determined to some measure by the purpose of the analysis, in this case computation of runoff from design-storms. As Mr. Paulson has shown, the effect of varying the assumed critical density will in most cases prove insignificant.

Regardless of the storage-factor used Mr. Paulson has presented a logical procedure for adjusting runoff for the delaying action of a snow-pack which is a marked improvement over the usual method of simply adding rainfall and simultaneous snow-melt and assuming this total to be the water available for runoff to the streams.

DIFFERENCES IN BASIN-CHARACTERISTICS AS REFLECTED BY PRECIPITATION-RUNOFF RELATIONS IN SAN BERNARDINO AND EASTERN SAN GABRIEL MOUNTAIN DRAINAGES

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(Published with the approval of the Director, Geological Survey, United States Department of the Interior)

Introduction

In interpretation and use of basic hydrological data as basis for planning any public works for conservation or control of water, there is great need for a careful and thorough analysis of the precipitation-runoff relations. Moreover, when such relations may have been worked out for one particular basin, experience has shown that extreme caution must be used in any attempt to apply these relations to another basin even though superficially the latter may appear to be comparable with respect to physiography, meteorological conditions, and all of the other elements which contributed to the relations established for the first basin.

Marked differences in basin-characteristics as reflected in the results of precipitation-runoff studies for five basins in the San Bernardino and Eastern San Gabriel Mountains have been found. These differences are explained and confirmed when considered in conjunction with the soils and geology of the basins, but without the latter information the application of the relations established in any one of the basins to any other would have been decidedly hazardous.

In the belief that the results found in these basins may be of interest and value, it is the purpose of this paper to present briefly a comparison of the precipitation-runoff relations in these five basins. The studies upon which this presentation is based are a part of an investigation currently being made by the Water Resources Branch of the United States Geological Survey in cooperation with the County of San Bernardino.

In the main the data given in this paper represent a brief summary only of some of the more outstanding features thus far covered in this cooperative investigation. Because large parts of the

San Bernardino and Eastern San Gabriel Mountains have not as yet been studied, a complete summarization for this region is, of course, not possible at this time.

Basin-characteristics

As essential to a better understanding of the relations later presented, Table 1 gives a comparison of the basin-characteristics for the five drainage-areas for which the relations have been developed. These are drainages of San Antonio, Strawberry, Deep, and Lytle creeks and of the West Fork of Mojave River. Deep Creek is the principal tributary of the Mojave River.

Table 1--Basin-characteristics for San Antonio, Strawberry, Deep, and Lytle creeks, and West Fork of Mojave River drainage-areas

Item	San Antonio Creek	Strawberry Creek	Deep Creek	West Fork Mojave River	Lytle Creek
Drainage-area, sq. miles	16.9	8.6	137	75	47.9
Altitude, feet					
Maximum	10,080	6,150	8,500	6,150	10,080
Mean	6,600	3,500	5,800	4,000	5,400
Minimum	3,400	1,650	3,050	3,050	2,200
Land-slope,					
Per cent	49	47	27	20.6	45
Main channel length,					
Miles	5.75	4.8	26.5	15.1	15.7
Slope, per cent	21	18	3.7	3.9	9.4
Average seasonal precipitation[a], inches	44.4	30.9	27.0	28.5	45.0
Average runoff, inches	19.9	8.1	8.6	9.6	13.5

[a]For period used in study.

It will be noted that the drainage-area of San Antonio Creek is the most elevated, with an average altitude of 6,600 feet. Deep Creek drainage is second in order of altitude, followed by those of Lytle Creek, West Fork of Mojave River, and Strawberry Creek. Of the five drainage-areas, those of San Antonio, Strawberry, and Lytle creeks are relatively steep in comparison with those of Deep Creek and West Fork of Mojave River. The drainage-areas of San Antonio and Lytle Creeks are adjacent. Likewise, Strawberry Creek Drainage-Area is adjacent to those of Deep Creek and West Fork of Mojave River. These areas represent both north and south exposures within a distance of less than 30 miles along the east and west range of the San Gabriel and San Bernardino Mountains.

Included in Table 1 are the figures derived for the average seasonal precipitation and the average runoff in inches. Those for the precipitation are for the periods only for which a computation of the basin-wide precipitation was made. It is indicated that relatively, San Antonio Creek drainage produces the greatest runoff and Strawberry Creek drainage the least. With slightly less precipitation than for Strawberry Creek drainage, both Deep Creek and West Fork of Mojave River drainages produce more runoff than does Strawberry Creek drainage.

Relationship between precipitation and runoff

Introduction--In order to arrive at a correlation between precipitation and runoff for a given area, it was the first endeavor in these studies to select a period of from 10 to 20 years in which not only could the concurrent data of precipitation and runoff be considered as reasonably reliable, but also in which there would have occurred the widest possible range in magnitude of events of storm and runoff.

For the San Antonio Creek drainage there is a 43-year record of runoff, of which the 20-year period 1921-41 was selected for analysis because of the better precipitation-data within this period. The record of runoff for Strawberry Creek drainage begins with December, 1919, and is continuous to date. The same 20-year period, 1921-41, was selected for the study of this area. For the Mojave River drainage the record of runoff is continuous from 1905 to 1922 and from 1929 to date. Supplementing this record, a number of the tributary areas were measured in the period 1892-1900. The limitations of the precipitation-data dictated the selection of the ten-year period 1905-15 for

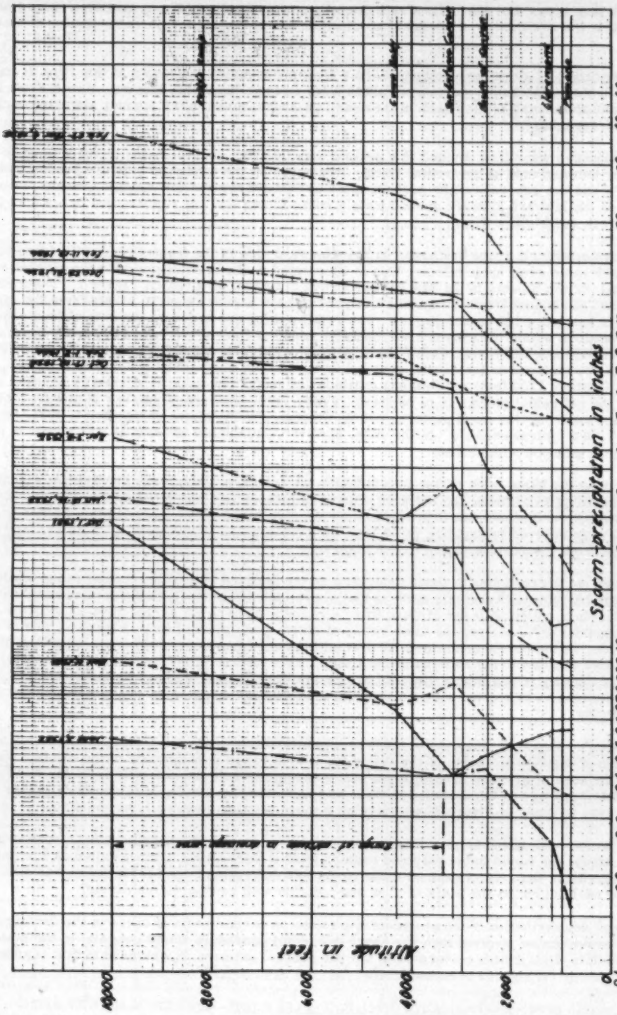


Fig. 1--Precipitation for selected storms in San Antonio Creek drainage-area

the study of this area. For the Lytle Creek drainage, records of runoff are available since 1904, but here again the availability of adequate precipitation-data limited the period selection to that of 1931-43.

Determination of storm-precipitation--As a first prerequisite in studies of this type, it was necessary to obtain the basin-storm precipitation for a large number of storms. Hence, from 250 to 400 storms were analyzed for each of the drainage-areas, about in the manner indicated in the following paragraphs.

The drainages were first divided in a general way into two groups--those on the windward and those on the leeward side of the frontal range. Drainages on the windward side are predominately south-facing and are represented by such streams as Strawberry and San Antonio creeks. Those drainages on the leeward side are predominately north-facing and are represented by such streams as Lytle Creek and Mojave River.

The precipitation in those drainages on the windward side of the frontal range was found to indicate considerable orographic effect. This is illustrated in the relationship between altitude and precipitation for ten storms in the San Antonio Creek drainage, as given on Figure 1. These storms were selected at random from 380 storms analyzed to show a wide range of events from the smaller to the larger and more infrequent storms. The relationships are based on the data of four precipitation-stations within the canyon area, namely, mouth of Canyon (altitude 2500 feet), San Antonio Canyon (altitude 3200 feet), Camp Baldy (altitude 4300 feet) and Kelly's Kamp (altitude 8200 feet), and of two stations on the debris-cone below the area of study. The latter stations are Claremont (altitude 1200 feet) and Pomona (altitude 850 feet). The general similarity of these diagrams for the individual storms is to be noted. There were, however, a number of storms that deviated somewhat from this usual pattern, and the diagram for the storm of October 1, 1931, included on Figure 1, is a typical example. In the main, however, substantial uniformity was shown in the change in precipitation with altitude.

In deriving the basin-wide storm-precipitation the drainage-areas were divided into a number of zones according to altitude, and the area of each of these zones was determined. The basin-wide precipitation for each storm was then obtained as the summation of the precipitation-values in each zone which were derived by applying to its area the precipitation corresponding to its average altitude as read from the altitude-precipitation diagrams.

Although the precipitation in those drainages on the leeward side of the frontal range would not of course be subject to analysis such as that above indicated, the availability of comprehensive precipitation-data collected in the Mojave River Drainage-Area in the period 1894-96 afforded an excellent opportunity to analyze the distribution of storm-precipitation on this leeward side of the frontal divide. In the period mentioned, 15 precipitation-stations were maintained along the divide and as far as 3.5 miles to the leeward of the divide. This section of the frontal divide is situated just north of the city of San Bernardino and has an average altitude of about 5800 feet. The precipitation-stations were located within a range of less than ten miles in an east and west direction along the divide.

As shown by Figure 2, analysis of these precipitation-data indicated a distinct and fairly uniform pattern of distribution north of the divide for a wide range in magnitude of the storms. In each case the zone of greatest precipitation was between one-half and one mile from the divide. For complete coverage of the drainage-area it was necessary to develop a series of diagrams similar in type to those of Figure 2 but covering a much greater distance from the divide.

Thus, in the case of the Mojave Basin, the drainage-area was divided into zones parallel to the divide except for zones in the extreme eastern part of Deep Creek drainage such as for Holcomb Creek. After the area of each of these zones was determined, the precipitation was distributed for each storm on the basis of area and location with respect to the divide.

Although determination of the storm-precipitation on certain parts of some of the drainages was considerably more involved than the above described procedure would indicate, in the main, the precipitation-distribution conformed to the two general patterns experienced in this region, as exemplified by the figures presented.

Relationship between accumulative precipitation and runoff--Once the basin-wide storm-precipitation was determined, study of the relationships between precipitation and runoff was first made by comparing accumulative precipitation and accumulative runoff. As a rule the accumulation was started with October 1, the beginning of the water-year and the approximate time of minimum

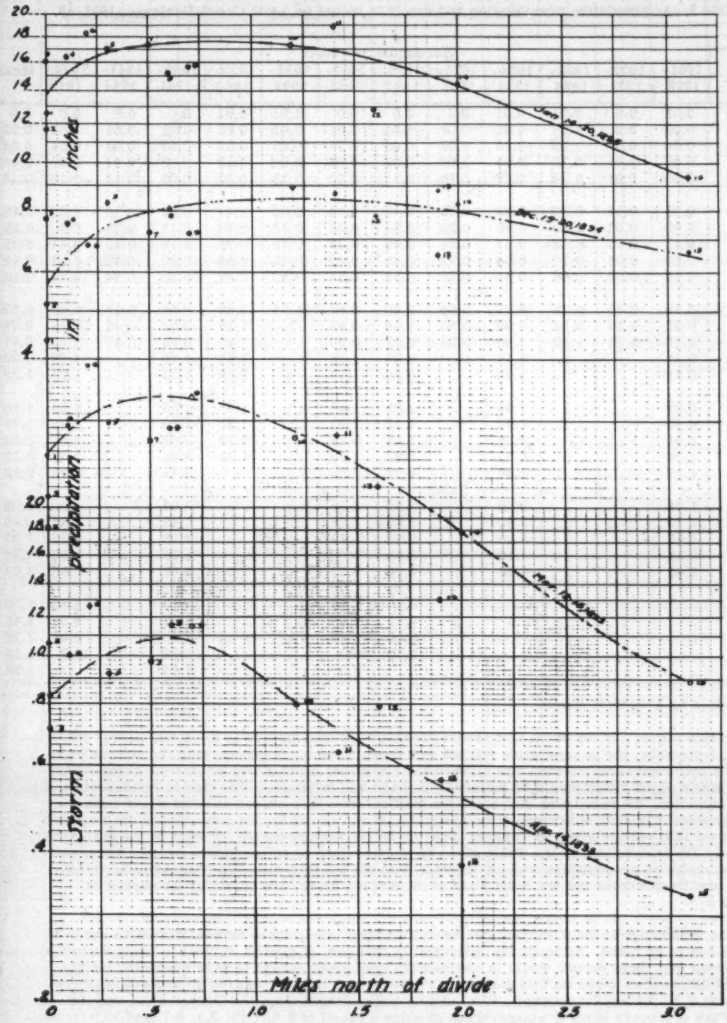


Fig. 2--Relationship between storm-precipitation and distance from the divide for representative storms

Table 2--Accumulative precipitation and runoff in inches on Lytle Creek Drainage, 1931-43

Accumulative precipitation	Accumulative runoff												Mean[a]
	1931-1932	1932-1933	1933-1934	1934-1935	1935-1936	1936-1937	1937-1938	1938-1939	1939-1940	1940-1941	1941-1942	1942-1943	
2	0.01	0.0	0.01	0.01	0.0	0.0	0.0	0.01	0.01	0.0	0.0	0.0	0.0
4	0.02	0.0	0.04	0.06	0.01	0.01	0.01	0.02	0.03	0.01	0.01	0.02	0.02
6	0.04	0.0	0.09	0.16	0.03	0.03	0.03	0.05	0.07	0.02	0.04	0.04	0.05
8	0.05	0.01	0.18	0.23	0.06	0.06	0.06	0.09	0.13	0.03	0.07	0.08	0.09
10	0.06	0.01	0.24	0.26	0.10	0.11	0.10	0.15	0.22	0.05	0.12	0.13	0.13
12	0.08	0.02	0.32	0.33	0.15	0.17	0.16	0.23	0.47	0.08	0.18	0.20	0.18
14	0.09	0.03	0.39	0.40	0.22	0.24	0.23	0.33	0.64	0.12	0.23	0.30	0.25
16	0.11	0.05	0.48	0.47	0.31	0.34	0.32	0.39	0.75	0.16	0.29	0.41	0.32
18	0.13	0.06	0.57	0.54	0.42	0.45	0.42	0.45	0.86	0.20	0.32	0.55	0.40
20	0.16	0.08	0.66	0.64	0.55	0.54	0.54	0.50	0.97	0.35	0.34	0.72	0.50
22	0.18	0.10	0.76	0.75	0.68	0.60	0.67	0.54	1.09	0.56	0.38	0.91	0.62
24	0.23	0.36	0.92	0.88	0.80	0.68	0.82	. . .	1.21	0.76	0.43	1.15	0.76
26	0.33	0.62	1.10	1.00	0.98	0.75	0.99	. . .	1.35	0.94	0.47	1.40	0.91
28	0.41	. . .	. . .	1.14	. . .	0.83	1.18	. . .	1.50	1.10	. . .	1.66	1.08
30	0.51	. . .	. . .	1.29	. . .	0.90	1.40	. . .	1.67	1.32	. . .	1.98	1.29
32	0.62	. . .	. . .	1.46	. . .	1.05	1.64	. . .	1.82	1.55	. . .	2.35	1.50
34	0.76	. . .	. . .	1.73	. . .	1.32	1.92	. . .	2.25	1.80	. . .	2.76	1.75
36	0.91	. . .	. . .	2.02	. . .	1.65	2.22	. . .	2.78	2.08	. . .	3.08	2.03
38	1.08	. . .	. . .	2.33	. . .	2.02	2.56	. . .	3.45	2.38	. . .	3.40	2.32
40	1.27	. . .	. . .	2.69	. . .	2.48	2.95	. . .	. . .	2.72	. . .	3.78	2.68
42	1.48	. . .	. . .	3.00	. . .	2.95	3.35	. . .	. . .	3.02	. . .	4.10	3.05
44	1.73	. . .	. . .	3.40	. . .	3.45	3.85	. . .	. . .	3.45	. . .	4.45	3.45
46	2.00	. . .	. . .	3.70	. . .	3.70	4.40	. . .	. . .	3.90	. . .	4.85	3.95
48	2.28	. . .	. . .	4.10	. . .	3.95	5.00	. . .	. . .	4.35	. . .	5.55	4.48
50	2.60	. . .	. . .	4.50	. . .	4.20	5.75	. . .	. . .	4.85	. . .	6.50	5.02
52	. . .	. . .	. . .	. . .	. . .	4.47	6.60	. . .	. . .	5.40	. . .	7.50	5.70
54	. . .	. . .	. . .	. . .	. . .	4.75	7.60	. . .	. . .	5.95	. . .	8.60	6.45
56	. . .	. . .	. . .	. . .	. . .	5.00	8.80	. . .	. . .	6.60	. . .	9.95	7.30
58	. . .	. . .	. . .	. . .	. . .	6.20	10.0	. . .	. . .	7.20	. . .	12.5	8.20
60	. . .	. . .	. . .	. . .	. . .	. . .	12.0	. . .	. . .	8.00	. . .	. . .	9.30

[a] Obtained by graphical means.

flow in this region. In the event that severe storms were experienced in the latter part of the preceding September, the accumulation started with these storms. In determining the accumulative runoff a sufficient time-interval was allowed after each period of storm so that the greater part of the storm-flood runoff would be included. If there was substantial flow due to antecedent seasonal precipitation, the runoff was corrected for the flow from this source as determined from the hydrographs. The data of accumulative precipitation and runoff for the Lytle Creek drainage for the period 1931-43 are given in Table 2. Similar tables were prepared for each of the drainages studied. The last column of the Table gives the mean values of accumulative runoff. These and the accumulative precipitation-values, together with the similar values for San Antonio, Strawberry, and Deep creeks and the West Fork of the Mojave River, are shown by the curves on Figure 3.

The wide range in the precipitation-runoff relations among these several basins as shown by Figure 3 is to be noted. Although the individual curves are, of course, subject to many errors, it is believed that these errors would in nowise have been great enough to have accounted for the marked differences shown on this diagram. These curves indicate that for an accumulative precipitation of 30 inches, for example, San Antonio, Lytle, Strawberry, and Deep creeks, and the West Fork of Mojave River drainage-areas produce a runoff of 1.0, 1.25, 3.8, 8.7, and 10.6 inches, respectively. All of the drainages are basically granitic with varying degrees of fracturing. Figure 3 would suggest that San Antonio Creek Drainage-Area has the greatest degree of fracturing and Deep Creek and West Fork of Mojave River the least.

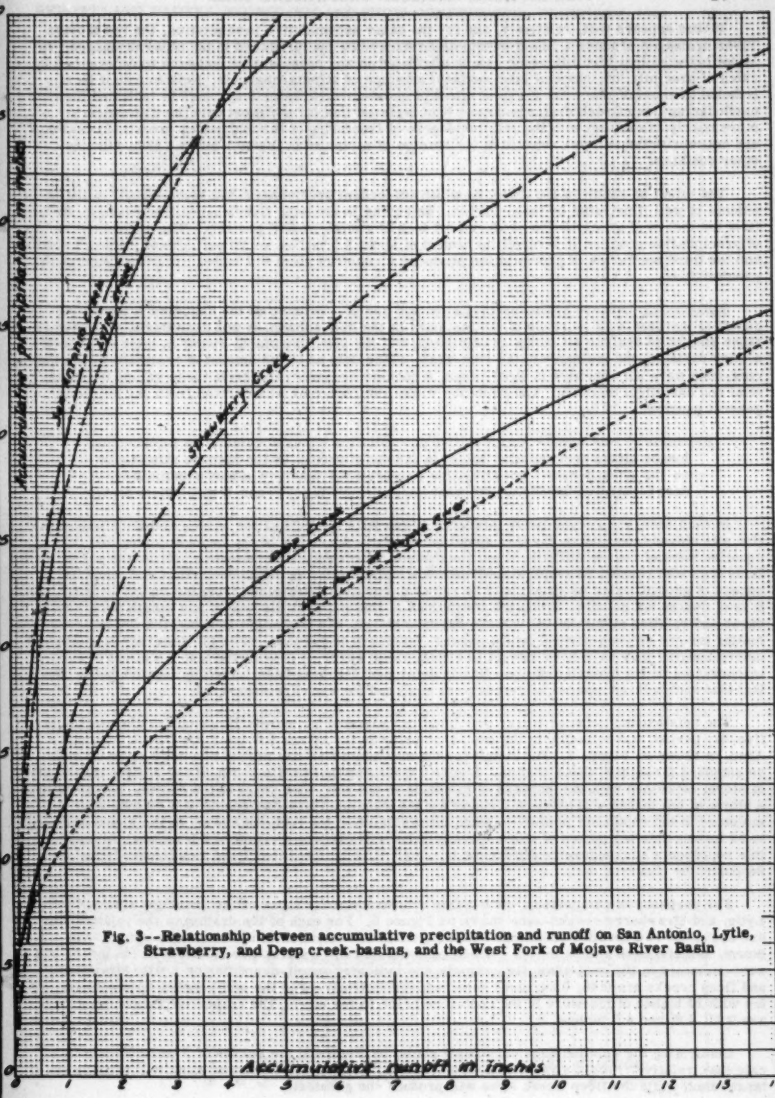


Fig. 3--Relationship between accumulative precipitation and runoff on San Antonio, Lytle, Strawberry, and Deep creek-basins, and the West Fork of Mojave River Basin

It thus appears that, relatively, and for the same accumulative precipitation, the two Mojave River drainages produce a runoff substantially exceeding that produced in the other drainages. It is not believed that this difference can be attributed in any considerable measure to differences in rates of precipitation, slope of land-surface, or slope of stream-channels. Neither can it be attributed to snowfall since the greatest effect of snow-cover in retarding runoff is indicated for the north-facing Deep Creek drainage-area. It is believed that for the most part the difference is more nearly associated with the relative degree of fracturing of the underlying granitic formations and hence with the relative capacities for storage of moisture in the soil-column than with any other condition.

The effect on runoff of the extent to which antecedent precipitation has stored water in the soil-column is well illustrated by these curves. Referring to the Deep Creek curve, for example, the first ten inches of precipitation produced 0.5 inch of runoff, or five per cent. The second ten inches of precipitation resulted in a runoff increment of about 2.5 inches, or 25 per cent of the precipitation, and the third ten inches of precipitation produced a runoff of about 5.7 inches, or 57 per cent of the precipitation.

Relationship between storm-precipitation and runoff--Because of the indicated tendency for runoff to increase with increase of the moisture in the soil-column, it was considered desirable in these studies to analyze all storm-precipitation and the resulting storm-runoff in their relation to a third variable, the moisture in the root-zone. Since data as to the amount of moisture within the root-zone were not available in most cases, it became necessary to derive these values by statistical and analytical methods. The retention within the root-zone was derived from the following general equation:

> Retention in root-zone = Accumulative precipitation minus accumulative interception-losses minus accumulative runoff in excess of ground-water seepage minus snow on the ground minus accumulative evaporation from snow minus accumulative deep penetration below the root-zone minus accumulative evapo-transpiration losses

In each case, the accumulative tabulation began with the first of the season and the above equation was solved from day to day throughout the season. A number of the items entering into this equation were of course difficult, if not impossible, of accurate determination. This was particularly true with respect to evaporation from snow. Such items as deep penetration and runoff in excess of ground-water seepage could be rather accurately determined from the runoff-hydrographs. It is of course not possible within the limitations of this paper to discuss at any length the procedures and relative merits of the various determinations, and this might well furnish the subject-matter for one or even several future papers. Suffice it to say that, while the accuracy of individual determinations may have been subject to considerable error, it is believed that the effect of such inaccuracies on the overall relations finally developed will have been largely mitigated due to the fact that such a large number of events were analyzed for each drainage-area.

The relationship between storm-precipitation (adjusted for snowfall), runoff for the maximum five-day period, and retention in the root-zone prior to the storm, for the Lytle Creek Drainage-Area, is shown on Figure 4. The runoff for the maximum five-day period was used more or less as standard throughout these studies. Figure 4 indicates that the flood-runoff for a given magnitude of storm increases with the increase of moisture in the root-zone prior to the storm. For example, a storm of ten inches will produce a runoff for the maximum five-day period of 0.44 inch when the moisture in the root-zone is zero. When the moisture in the root-zone prior to the storm amounts to 32 inches, this ten inches of storm-precipitation will produce a runoff of 6.5 inches. Although this represents a considerable difference in runoff, it is believed that these results are fairly well supported by observed data.

For purposes of comparison, these same relationships for three of the drainage-areas--Deep, Lytle, and Strawberry creeks--are shown on Figure 5. For each of the drainages the relationships are shown for two specific conditions with respect to the retention in the root-zone prior to the storm, namely, zero and 12 inches. It will be noted that for a storm-precipitation of ten inches and zero-moisture in the root-zone, for example, the indicated runoff-quantities on Lytle, Strawberry, and Deep creeks are 0.45, 0.84, and 1.4 inches, respectively. For the same storm-precipitation but with 12 inches of moisture in the root-zone prior to the storm, the respective runoff quantities are 0.71, 2.0, and 4.0 inches.

Confirming the relationships previously shown by Figure 3, the curves of Figure 5 again indicate that, relatively, for a given storm-precipitation, Lytle Creek Drainage-Area will produce the least runoff while the Deep Creek Area will produce the greatest.

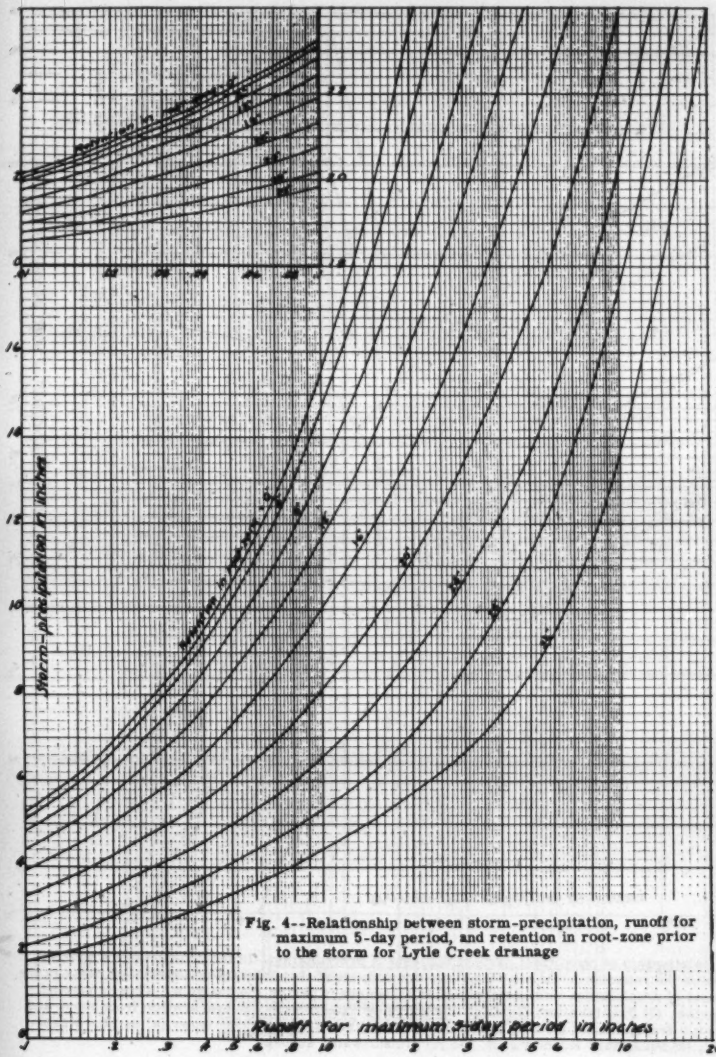
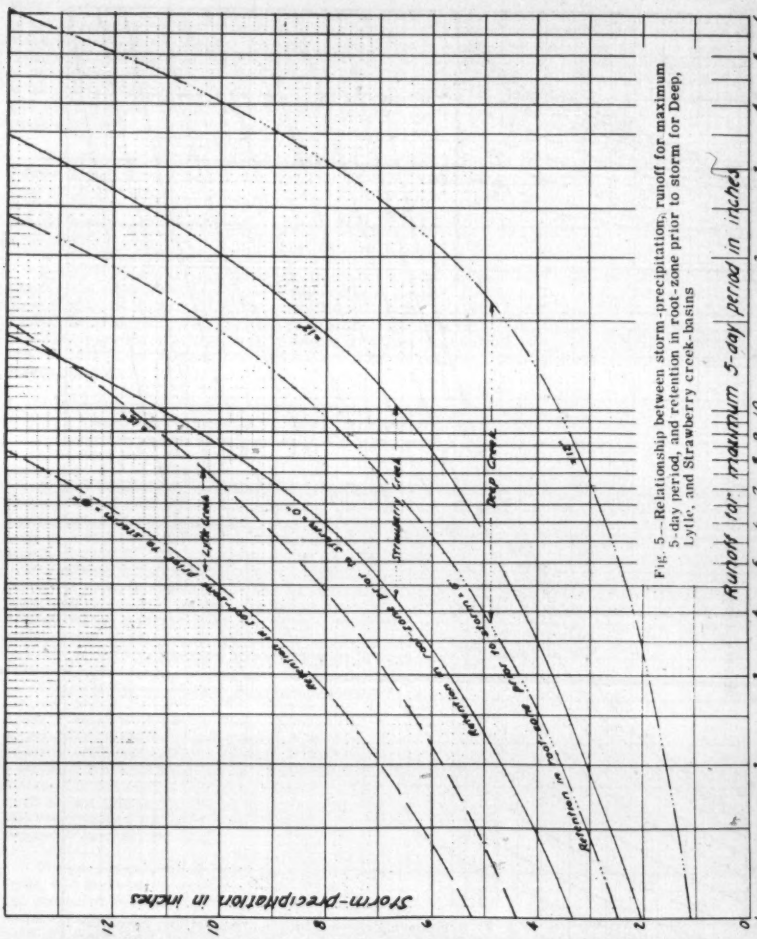


Fig. 4--Relationship between storm-precipitation, runoff for maximum 5-day period, and retention in root-zone prior to the storm for Lytle Creek drainage


Storm-precipitation in inches
Runoff for maximum 5-day period in inches
Deep Creek
Strawberry
Lytle
Fig. 5--Relationship between storm-precipitation, runoff for maximum 5-day period, and retention in root-zone prior to storm for Deep, Lytle, and Strawberry Creek-basins

Relationship of constituent parts in disposal of precipitation--In the solution of the equation by which the retention in the root-zone was derived, all of the elements or constituent parts in the disposal of precipitation were determined as a necessary part of the analysis. These elements comprise: (1) Precipitation; (2) water-losses by (a) interception, (b) evaporation from snow, and (c) evapo-transpiration; (3) deep penetration; and (4) runoff of the three types (a) surface storm-runoff, (b) subsurface storm-runoff, and (c) ground-water seepage.

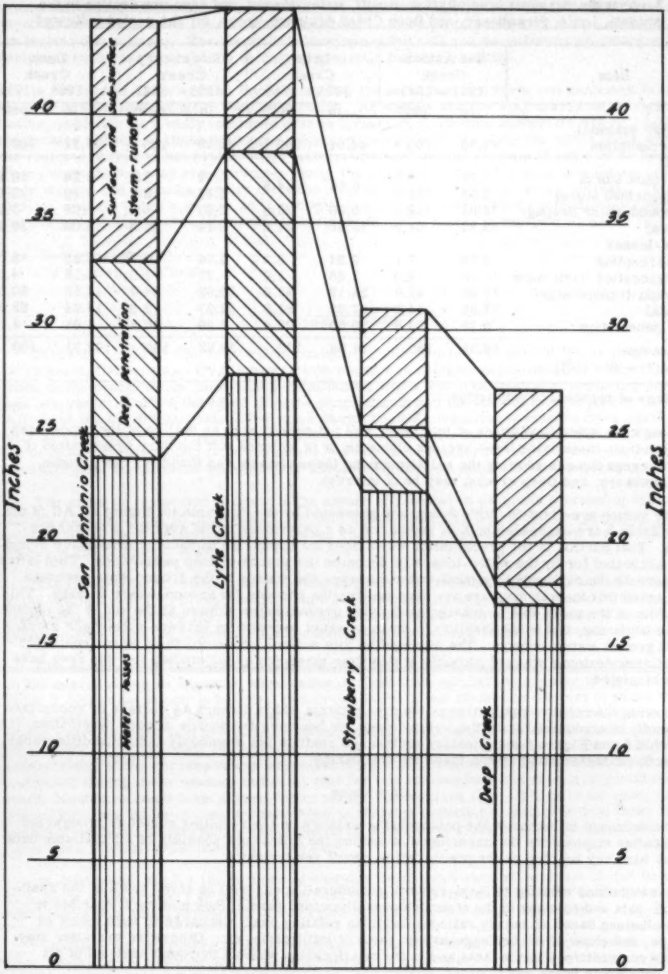


Fig. 6--Disposal of seasonal precipitation in San Antonio, Lytle, Strawberry, and Deep creek-basins

Table 3--Average seasonal precipitation, runoff, water-losses, and deep penetration in the San Antonio, Lytle, Strawberry, and Deep Creek drainage-areas, for the period indicated

No.	Item	San Antonio Creek 1921 - 1941		Lytle Creek 1931 - 1943		Strawberry Creek 1921 - 1941		Deep Creek 1905 - 1915	
		in	pct[a]	in	pct[a]	in	pct[a]	in	pct[a]
1	Average seasonal precipitation	44.36	100	44.98	100	30.92	100	27.11	100
	Runoff								
2	Surface storm	1.76	3.9	6.66	14.8	1.59	5.1	2.96	10.9
3	Subsurface storm	9.52	21.5			3.86	12.5	6.10	22.5
4	Ground-water seepage	8.65	19.5	9.00	20.0	2.69	8.7	.94	3.5
5	Total	19.93	44.9	15.66	34.8	8.14	26.3	10.00	36.9
	Water-losses								
6	Interception	3.16	7.1	2.34	5.2	1.94	6.3	2.36	8.7
7	Evaporation from snow	1.76	4.0	1.36	3.0	.31	1.0	1.15	4.2
8	Evapo-transpiration	19.06	42.9	24.12	53.6	20.02	64.7	13.53	50.0
9	Total	23.98	54.0	27.82	61.8	22.27	72.0	17.04	62.9
10	Deep penetration	9.10	20.6	10.50	23.4	3.20	10.4	1.01	3.7
	Summation [(5) - (4) + (9) + (10)]	44.36	100	44.98	100	30.92	100	27.11	100

[a]Percentage of seasonal precipitation.

Although the space limitations of this paper will not permit even an outline of the procedures and computations in deriving these various elements, it is believed that the bare presentation of the final average figures showing the relation among these elements as found for San Antonio, Lytle, Strawberry, and Deep creeks, may be of interest.

These values are given in Table 3, and are presented by the diagrams on Figure 6. All of the values in Table 3 are expressed both in inches and as a percentage of the average seasonal precipitation. That portion of the precipitation which does not appear as surface or subsurface storm-runoff is accounted for by the water-losses or becomes the source of deep penetration. This latter item represents the recharge to ground-water storage--the source of the ground-water seepage. It will be noted that in each drainage the deep penetration exceeds the ground-water seepage. This difference is, in the main, due to greater basin-wide ground-water storage at the end of the period than at the beginning, and to the inability to make an exact segregation between subsurface storm-runoff and ground-water seepage. The segregation into surface and subsurface storm-runoff for the Lytle Creek drainage was not possible at this time inasmuch as the studies for this area have not been completed.

In showing the relative proportion of the precipitation which appears as surface or subsurface storm-runoff, is accounted for by the water-losses, or becomes the source of deep penetration, the data of Table 3 and Figure 6 significantly explain and confirm the previously indicated differences in the runoff-characteristics among these several basins.

Conclusion

The wide-range influence of the basin-characteristics on the resulting runoff as brought out in these studies emphasizes the importance of making the fullest use possible of all available data which may have any bearing on the precipitation-runoff relationships.

In investigations relating to flood-control, consideration can well be given to all of the available runoff-data and to many of the other features discussed herein, thus making it possible to check conclusions based on purely rational formulas relating peak-discharge to such items as size, shape, and slope of the drainage-areas, rates of infiltration, etc. Otherwise the latter may be entirely contradictory to the facts and to the relationships which a thorough analysis of all available data would bring out.

Only by such studies as have herein been described does it seem possible to arrive at a reasonably accurate basin-wide evaluation of those important elements, retention in the soil and ground-water storage and release. From an analysis of data covering only a few years of record

the nature and extent of the deep penetration, and correspondingly the rates and magnitude of ground-storage may be fairly well established. An example of this is the finding of little deep penetration and hence the indication of low rates and amounts of storage as a part of the analysis for Mojave River Basin. The general shallowness of the soil and the unfractured nature of the underlying granite are undoubtedly largely responsible for this condition.

In the case of Lytle and San Antonio creeks, the much more uniform and sustained flow is indicative of substantially more deep penetration. An equally shallow soil-mantle is, in these basins, underlain by a badly fractured granite formation of a highly absorptive nature. Although the greater altitude of these drainages would indicate greater snowfall, the effect of the latter on the regimen of flow is not evidenced by material changes during seasons of little or no snowfall. Even though these areas are extremely steep, the talus deposits on the mountain slopes and the large stream-bed deposits greatly increase the opportunity for ground-water storage. The combination of these factors is such as to present, therefore, the somewhat contradictory condition that the least concentration of runoff is experienced in the basins of steepest slope.

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DISCUSSION

ROBERT L. WING (California Department of Public Works, Division of Water Resources, Sacramento, California)--This is a very interesting and valuable paper because it emphasizes a phase of the precipitation flood-runoff relationship which has been somewhat neglected during the past few years. That is the effect of prior precipitation and the amount of moisture in the soil-column on the infiltration-rate. The paper shows the wide variation in runoffs from equal rainfalls on watersheds which superficially appear to be quite similar and concludes that this variation is the result of differences in the structure and degree of fracturing of the underlying bedrock and the consequent variation in the amount of water which may be stored in the soil-column.

The paper as presented is more in the nature of a report of progress discussing various studies which are still in progress rather than a final report on a finished investigation. Unfortunately it has been so condensed that it does not present a complete picture of any of the various phases of the problems studied.

Except for general statements no geological data are presented by which definite evaluations of the various geological features of the several drainage-basins could be made. While such evaluations are not absolutely necessary when studying areas for which records of runoff are available they would be indispensable in estimating runoffs from unmetered areas.

The variations in the rainfall-runoff relationships for the several drainage-basins are based on the curves shown in Figure 3, which were derived from tabulations similar to those shown in Table 2. Just what runoff is included in this tabulation is not defined in the text in which it is stated "the greater part of the storm-runoff would be included". In the Table it is noted that in practically every year the last two inches of seasonal rainfall produced the maximum increment of runoff and that in two seasons, 1937-38 and 1942-43, this increment amounted to 100 to 127 per cent, respectively, of the corresponding increment of rainfall. Analysis of the distribution of rainfall and runoff during these seasons indicates that for this to have been the case a large amount of the runoff must have come from ground-water rather than surface flow. If this is the case, an analysis such as this, while of considerable value in studying seasonal or periodic total flows when possible yields for water-supply are in question, would be of much less value in studying flood-flows when channel-capacities are in question.

It is believed that for the purpose of studying flood-flows such an analysis should be confined to surface storm-runoff. In southern California areas, particularly, the total ground-water seepage will always be a small proportion of any crest or short-period major flood-runoff.

The analyses of storage in the soil-column or, as it is termed in the paper under consideration, "retention in the root-zone" seem to present a much more favorable approach to the determination of the effect of prior precipitation on the rainfall-runoff relation and also show similar differences between runoffs from the Mojave River basins and the Lytle Creek Basin.

It is noted that in these studies the soil-column has apparently been divided into two sections, the root-zone and the area of deep penetration, and that the ground-water runoff has also been

divided into corresponding classifications--subsurface storm-runoff, apparently seepage from the root-zone, and ground-water seepage apparently from deep penetration. In areas such as southern California where often periods of a month or more may interpose between storms of appreciable magnitude it is possible for two or even more zones of saturation to occur in a deep soil-column. Figure 4 shows storage in the root-zone up to 32 inches of water. Assuming 20 per cent of voids in the soil, this means soil saturated to a depth of over 13 feet. This is deeper than is usually considered to be the root-zone of trees, much less of the brush with which much of the drainage-areas considered are covered.

Inspecting the data presented in Table 3, it is noted that while Lytle and San Antonio creeks both have about 45 inches of rainfall and both yield about nine inches of ground-water seepage, Lytle Creek has less storm-runoff and correspondingly greater evapo-transpiration losses. This would seem to indicate that while the Lytle Creek Basin absorbed water as easily as the San Antonio Creek Basin, it yielded it to the stream-channels less freely from the root-zone, but at an equal rate from the zone of deep penetration. It seems possible that the subsurface storm-runoff has been either underestimated on Lytle Creek or overestimated on San Antonio Creek. On Deep Creek the subsurface storm-runoff is estimated to be larger than on Lytle Creek in actual volume and to be a larger percentage of the precipitation than on San Antonio Creek. This would seem to indicate an equal storage-capacity in the root-zone and also an equally free discharge. Also, in percentage of total precipitation, evaporation-transpiration losses although slightly less than on Lytle Creek are considerably larger than on San Antonio Creek. The essential differences between the areas seem to be a higher surface storm-runoff and almost no ground-water seepage from the Mojave River areas. This would seem to indicate equivalent root-zone storage and possibly easier discharge-capacity to stream-channels but an almost complete lack of deep penetration in the Mojave River basins.

Although this analysis indicates much greater storm-runoffs from the Mojave River basins, the major portion of these storm-runoffs are from subsurface flows occurring some time after the crest-flows of the flood have passed. It does not seem that the analysis has demonstrated, conclusively, that the larger storm-surface runoffs result from differences in the storage-capacity of the soil-column.

The analyses in this paper have been based on only five stream-basins--a small number on which to establish general laws of hydrology. Consequently before the relations shown can be accepted as of universal application, it should be demonstrated that no other factor could have produced the relations found. In this case, it should be noted that the areas showing high runoffs lie on a north slope facing the desert while the areas of low runoff lie in a southern drainage facing the sea, that the areas of low runoff both lie to the east of the areas of high runoff, that, historically, all storms producing major floods in one basin have not produced equivalently high flows over the other basins, and that the periods of record of study on the two groups of basins are not coincident. For these reasons it seems to the writer that, if possible, proof should be presented that the greater runoffs over the Mojave River basins are not the result of a consistently more intense storm-pattern bringing more rainfall at rates in excess of the infiltration-rate of the surface soils.

C. B. MEYER (California Department of Public Works, Division of Water Resources, Sacramento, California)--This is a very interesting and valuable paper. It is valuable because it shows the wide variations in the runoff which may be obtained from watersheds which superficially appear very similar. It emphasizes again the danger in basing estimates of probable runoff on rainfall alone. The conclusion is reached that the wide variation in the runoff between the different basins studied is caused by variation in the amount of fracturing in the granitic rocks which underlie all of the basins, but no method is advanced for determining the amount of fracturing in approaching the study of a basin for which no records of runoff are available.

Figure 1 shows the variation of the precipitation with the variation of elevation on the windward side of the mountains for a number of the storms studied. This Figure indicates an increase in precipitation up to a maximum elevation of 10,000 feet. In the Sierras, the theory has been advanced that precipitation increases up to an elevation of 6,000 feet on the windward side and thereafter decreases up to the summit. Figure 2 shows the variation of the precipitation with distances from the crest of the mountains for the leeward watersheds for various storms studied. This Figure shows an increase in the precipitation reaching a peak at a point from one-half to one mile to the leeward from the crest of the mountains and thereafter decreasing. Unfortunately the storms shown on Figure 1 are not the same as those shown on Figure 2, so it is not possible to determine if the precipitation actually reaches a maximum at a point one-half to one mile to leeward of the crest and not at some elevation below the crest on the windward side as is usually assumed.

A study was made of the effect of variation of the moisture in the soil-column and its effect on storm-runoff. Figure 4, "Relationship between storm-precipitation and runoff for maximum five-day period, and retention in root-zone prior to storm for Lytle Creek drainage", was developed from this study. The Figure shows a series of curves from 0 to 32 inches labelled retention in root-zone. If the recoverable water amounts to 20 per cent of the soil-volume, this would mean a root-zone in excess of 13 feet, a much greater depth than is usually considered to be the root-zone of trees. Perhaps these curves should have been labelled retention in soil-column.

While the amount of soil-moisture prior to a storm is an important factor influencing the amount of storm-runoff, another factor which does not appear to have been given any consideration in the studies reported in this paper is the concentration or variation in rate of rainfall within the five-day storm-periods studied.

In Table 1, the average runoff from Lytle Creek is given as 13.5 inches while in Table 3 it is 15.66 inches. However, it is not clear whether the same period of record was used in Table 1 as was used in Table 3. The average runoff from Deep Creek is given as 8.6 inches in Table 1 and 10.0 inches in Table 3. The average runoff for the other two streams agrees closely in the two tables. In Table 2, columns headed "accumulative runoff" probably should be headed "accumulative storm-runoff".

The paper has been purposely condensed but its usefulness would be greatly enhanced if at least a sample of the computations by means of which the rainfall was divided into surface and subsurface runoff, deep penetration, interception, evaporation and transpiration losses was included.

HARLOWE M. STAFFORD and HAROLD C. TROXELL--It is indicated that most of the discussion of this paper has arisen from the difficulty of properly interpreting the data presented, because of necessity the latter were entirely too condensed and it was not possible to include much of the supporting data and explanatory material.

The data on runoff given in Table 1 are for the entire period of record, which ranges from 20 to 40 years, while the runoff data in Table 3 are for the periods indicated in the Table.

The accumulated runoff given in Table 2 and plotted on Figure 3 represents the entire runoff (including storm-surface runoff, storm-subsurface runoff, and ground-water seepage) from the beginning of the season less that portion of the base-flow, or ground-water seepage, due to antecedent seasons. Inasmuch as the runoff in this Table and Figure is concurrent with the precipitation, except for a short time-lag, it is believed that it gives a fairly complete indication of the response of the area to flood-producing precipitation. As derived, the accumulation of runoff and precipitation ceased with the last sizable rain of the season, usually in April, thus excluding a large portion of the subsurface runoff and ground-water seepage in certain of the areas. The great difference in runoff between the West Fork of the Mojave River and San Antonio Creek drainage-areas for the same accumulative precipitation represents the difference in retention. Thus, unless overshadowed by a great difference in precipitation, the areas showing the smaller retention are considered to represent those of greater flood-hazard.

It would appear that often the ability of these mountain areas to absorb and store moisture may be greatly underestimated. For example, Table 2 shows that in 1940-41, with an accumulative precipitation of 60 inches in the Lytle Creek Area, the retention within the drainage amounted to 52 inches. It is believed that a large part of this moisture is within the root-zone, in that it is subject to water-losses of which the loss by evapo-transpiration is by far the largest part. This ability of the mountain areas to retain large quantities of moisture within the basin greatly reduces the significance of instantaneous rates of rainfall and periods of concentration.

The data presented in Table 3 are not alone sufficient to warrant the conclusion that the storage-capacities within the root-zone of Lytle and Deep Creek basins are nearly equal. A comparison of the very rapid rate of release of subsurface storm-runoff in the Deep Creek Area with the highly sustained subsurface storm-runoff in Lytle Creek indicates substantially greater storage-capacity for this type of runoff in the latter area.

Fully appreciated by the authors is the desirability and importance, as brought out in the discussion, of the geological and soil data, not only in support of the conclusions reached, but also as of great value in applying the results of these studies to other drainage-areas. Although not possible of presentation in this paper, it is to be noted that considerable data of this nature are being secured in the course of these studies and that in the final report thereof it is contemplated that there will be an appropriate presentation and correlation of these data.

POST-WAR MANAGEMENT OF WESTERN FORESTED WATERSHED-LANDS FOR WATER-YIELD

C. A. Connaughton and H. G Wilm

As we come in contact with post-war plans in the West, most of us are impressed with the stress being placed on development and utilization of water. Every crossroads village seems to have a plan for some project of water development. Cities, counties, States, and regions all have ambitious plans involving use of water, with the zenith approached by the Federal Government in a recently announced three-billion-dollar reclamation plan.

Such a strong accent on water seems to indicate that, in the post-war period, water-utilization in the semiarid West will become more closely associated with the general welfare than ever before. Moreover, it indicates that everyone responsible for any phase of water-yield or regulation will have new and added responsibilities and obligations.

To the foresters of the West this situation offers a particularly outstanding and clear-cut duty, namely, that of developing and implementing practices of management which will insure optimum yields of usable water from forest lands. In the aggregate, about 225 million acres of the most productive water-yielding land in the West are under forest administration. About 65 per cent of this land has a major watershed-influence and another 25 per cent has a moderate influence. As a consequence the forester is faced by serious obligations if his plans and actions are to fulfill the responsibilities involved.

There is much precedent, of course, for the management of forest lands for water-yield, as some aspects of this job have been recognized and practiced by foresters for many years. In the past, however, emphasis has been placed for the most part on watershed-protection. Now, with the accumulation of knowledge on restoration and improvement of watersheds, these phases of the problem of forests and water-yields will loom larger in the post-war years than ever before.

Watershed-protection--In considering the various aspects of post-war forest management for water-yield, we can see that attainment of adequate protection is the first step in any program. This means, first of all, protection from fire, as fire is still the greatest single agency of damage to the forest. When fires sweep over forest land the trees and associated vegetation are often destroyed and even the organic matter in the surface soil may be consumed. Such devastation sets the stage for floods and erosion with resultant damage to land and improvements, both on the watershed and in the areas depending on it for water-supplies. Although large storms have shown that there is a definite upper limit to the capacity of vegetation to minimize floods, the general benefits of a forest cover have been demonstrated so frequently that the desirability of protecting valuable watershed-areas from fire is beyond any reasonable question.

The general relation of forest fires and water, so graphically portrayed in southern California, can be duplicated at many places throughout the West, from the eastern slope of the Rocky Mountains across the entire forest belt to the Pacific Coast. It has been so evident, in fact, that most problem areas have been given some protection; but in the post-war years fire-control measures must be intensified on public and privately owned lands alike, until we have reasonable assurance that every possible effort has been made commensurate with investments for water-utilization.

Protection of forest land from other harmful influences such as over-grazing will be intensified in the post-war era. For many years administrators of the national forests have been working on this particular problem and have attained considerable success; but conditions even on some of the national forest lands are still unsatisfactory. Other lands are much worse, with the result that accelerated runoff and erosion are occurring on large areas, with damaging effects on the usability of stream-flow.

Intensified protection of the forest from insects and diseases will also be developed after the war. Generally speaking, these destructive factors are not so closely associated with water-yield as are fire and over-grazing, because they do not ordinarily cause complete destruction of both the trees and the understory of lesser vegetation. The residual understory continues to exert some beneficial watershed-effects even though much of the timber may be destroyed. The seriousness of depredations by insects is illustrated, however, by very new epidemics of insects on an important tributary of the Colorado River, where 125 million board-feet of timber have been killed in the last two years and the epidemic is still spreading rapidly.

Protection against destructive timber-cutting on important watersheds is a major task at any time. In some places timber-cutting on both public and private land is being handled without damaging results; but on many privately owned lands bad logging-practices are definitely injuring forest-water relations. To correct this situation, practices must be required which will protect the public's interest in these lands. This will call for some measure of public control, which takes cognizance of the need for maintaining acceptable watershed-conditions.

Watershed-restoration--Following adequate protection of the forest, the next essential step is rehabilitation of areas which have been previously damaged or depleted. Where fire or destructive logging has removed the forest cover to a point where the hazards of flood and erosion have been increased, a big job of upstream engineering must be included in watershed-management activities.

Upstream measures on forest land will include a variety of tasks, ranging from reforestation to flood and erosion-control structures. The object of this work will be to improve the productive capacity of the land for the growth of timber and to safeguard and regulate stream-flow. Included also will be the repair of damage wrought by grazing to forest land, which may call for revegetation as well as engineering structures.

In many areas where the forests have been destroyed, it will be desirable to restore the original cover by reforestation. This is not universally true, however, since often the original forest-cover may be replaced with grass of sufficient density to prevent accelerated erosion; although it is possible that peak-discharges are less successfully regulated by grassland than by timber. Thus it may be desirable to retain a grass-cover wherever--as is commonly the case in the Rocky Mountains--water-yield is more important than timber-growth, and where stream-regulation may be obtained by reservoirs. Whatever the optimum cover-type may be, the forest manager will be obliged to include its attainment in his plans, even though it may mean reduction of the original forest acreage.

Watershed-improvement--Extending the thought that a dense forest may not always provide the best watershed-cover, we come to a related idea which has not been emphasized in the past, but which deserves a great deal of consideration in post-war management of forests. This is the concept that virgin stands of timber can be materially improved for water-yield by employing proper practices in management. Such improvement may be accomplished by careful thinning of the forest-cover, to reduce the consumption of water by interception, evaporation, and transpiration, while leaving a forest dense enough to protect the soil from deterioration and erosion. Obviously this kind of management applies only to the large areas of forested watershed-land where water-yields are unusually important, and where floods and erosion present a relatively slight hazard--areas such as the water-yielding forests of the high Rocky Mountains, the Sierra Nevada, and other water-producing mountain areas. This concept does not apply to areas like the San Gabriel Mountains of southern California or the Wasatch Front in Utah, where protection against floods and erosion is the paramount consideration.

To illustrate the possibility of improving the forest for water-yield, results of a current study in Colorado provide illuminating facts. In this study a cut-over forest of lodgepole pine was shown to provide much more favorable conditions for the winter storage of snow than those in a virgin forest. Actually 26 per cent more snow was found in stands from which all trees larger than 9.5 inches in diameter had been removed in accordance with sound forestry practices. In addition, 33 per cent more moisture reached the forest floor from spring and summer rainfall in these heavily cut-over stands. When other factors, such as evaporation from the soil and snow in these two stands, were introduced into the comparison, in the aggregate 31 per cent more water was available for stream-flow from the cut-over area than from the virgin forest. And, in a three-year period after treatment, no visible erosion was caused by the timber-cutting operation.

The results of this experiment have not yet been evaluated in terms of actual stream-flow; but an early study at Wagon Wheel Gap, Colorado, indicates that stream-flow can be expected to respond to treatment of the forest. In the Wagon Wheel Gap study complete removal of the forest-cover from a small watershed was found to increase total yields of water 15 per cent for a seven-year period after the cutting operations. This increase was minimized by the fact that the original forest was not heavy and that, after removal of the forest, rapid recovery resulted from the sprouting of a dense stand of aspen. From both these studies we can estimate with reasonable conservatism that proper cutting of dense forests of the Rocky Mountains according to sound forestry

practices may increase tributary stream-flow as much as 20 to 25 per cent without damage to the watershed, at a profit derived from sale of the timber-products, and with methods that will insure satisfactory regrowth of commercial timber.

As remarked above, this practice of forest cutting to improve water-yields cannot be applied indiscriminately. Where flood-hazards are high and erosion is easily induced, exactly the opposite practice might be desired--that is, no timber should be cut, or at least only that which has passed maturity. At all times adequate safeguards must be employed; and one post-war task in forest management will be to classify lands on which various cutting practices may safely be applied for the improvement of water-yields.

It should be stressed that the practice of improving water-yield by timber-cutting achieves the double purpose of harvesting a crop of timber while enhancing stream-flow. By this means an economic gain can be provided for both the forest-land owner and the water-user. Some further study is necessary to work out the application of these methods in detail to all types of forest and climatic conditions, but knowledge is sufficiently advanced at present to indicate their potentialities in the post-war years.

Certainly in selecting timber-cutting methods on many watersheds in the post-war period the use of the runoff to be derived will play a prominent part. If, as we have just indicated, floods and erosion offer no particular problem and regulation of flow is achieved by reservoirs, the cut should be frequent and as heavy as may be compatible with acceptable economic returns. If natural regulation of flow is more important than water-yield, cutting should be lighter and a fairly complete forest-canopy should be maintained. If flood- and erosion-hazards are high, cutting must be held to a minimum--no more than enough to keep the forest healthy and productive. Selection of specific practices will be governed by appraisal of local conditions and the judgment of foresters intimately familiar with all factors.

Public acquisition of forested land--Somewhat apart from actual on-the-ground forest management, but greatly influencing it, is the need for public acquisition of important water-yielding land throughout the West. Of the western forested lands in private ownership, at least 60 million acres have major influence on watersheds, and 20 million have moderate influence. On some of these lands existing methods of management satisfy the public interest, including that of water-users. On a larger percentage, however, management is not being practiced to the best public interest. Where watershed-values on these lands are now being damaged or may suffer misuse in the future, public acquisition in the interest of the general welfare is essential.

There has been some effort to classify such lands for public acquisition, and estimates of the areas involved are available for several regions. However, in the post-war period surveys and plans should be developed to appraise accurately the place of water-yield in the resources of these lands and then to work out the necessary mechanics to insure their acquisition by the public. After they are placed in public ownership, many essential requirements of management can be attained which cannot be met in private ownership.

The forester and the water-user--In spite of the great importance of water-yield in the management of western forested land, full consideration of requirements of watershed has not always been met in perfecting plans and practices of management. This is true on both public and privately owned lands, largely because water-users have not taken sufficient interest in the relation of forestry to water-supplies. Too frequently, the water-user is remote from the point on the forest where stream-flow originates, and he fails to express his interest in the use of the forest as it may influence water-supply. The forester on the ground, on the other hand, is subject to many local pressures and demands, and although he may have the interest of the water-user strongly at heart, he may actually slight the less tangible water aspects of his job.

Another reason why watershed-values have often been neglected in forest management is that water, in contrast to timber and other products, seldom brings a cash return to the forest manager. This makes it difficult to translate watershed-management accomplishments into direct monetary returns, with the result that economic justification for special watershed-measures may be difficult to establish. As a further reason, once the water is collected in the stream the forester's legal responsibility for its management is usually passed on to someone else. This is not necessarily a serious situation, but it is a contributing factor which should be recognized by water-users to whom the forester must look for support of his practices of management.

Especially in the post-war development of water-resources, these various circumstances mean that the forester and water-user should seek mutual advice and counsel. Each has something to contribute to management of watershed, and each has a general understanding of the other's problem; but each needs to acquire a more intimate appreciation of the other's objectives. The forest and water-yield are linked inseparably--the forester and water-user should be also.

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DISCUSSION

JOSEPH KITTREDGE (University of California, Berkeley, California)--The questions which this paper raises in my mind are probably of a kind that supporting evidence, if it were available, would be conflicting for different conditions and hence not suitable as a basis for generalization. However, some of these questions have considerable interest even if proof is not yet conclusive.

One item mentioned as requiring more attention by foresters from the viewpoint of water-regime is intensified protection of the forest from insects and diseases. As the authors point out, these epidemics may destroy most of the forest trees of one or two species but rarely is all of the vegetation on an area attacked. As the trees are killed, the grasses and herbs and shrubs rapidly occupy the space so that the surface of the ground is not at any time denuded. Under these circumstances it is doubtful whether even the worst epidemics cause sufficient erosion to reduce the usability of the water. Not only that but it might well be that the smaller vegetation which replaced the trees would use less water and consequently the yield of water from the area would be increased. This would be an instance where the unquestionable advantage of controlling the epidemic from the point of view of production of timber might conflict with the objective of maximum yield of usable water.

Another suggestion is made that bad logging-practices are injuring forest-water relations and that some measure of public control is essential for correction of the situation. The bad logging-practices must be chiefly downhill skidding of logs. Can public control eliminate downhill skidding? I have seen one example on the Navajo Indian Reservation in northern New Mexico where logs were being skidded along the contour on a gentle slope so that the skidding trails formed contour-ditches and undoubtedly promoted conservation of water. In steep mountainous country, however, such as prevails where most of the logging is being done in the west, is it possible to avoid downhill skidding in some form? The main routes of transportation are necessarily on a low grade and for that reason follow the stream-bottoms. Much of the timber is up on the slopes and must be brought down. It cannot be brought down in any practicable way with horses or tractors or low-line cables without creating more or less steep skidding trails in which water will concentrate and cut. It may be that some form of the high lead donkey logging which was considered a highly destructive form of logging for future production of timber might actually be organized to create less channels for erosion than other logging methods. Downhill skidding is permitted in logging jobs on existing national forests and it seems quite unlikely that it would be prohibited under public control elsewhere. In this connection it may also be pointed out that most of the logging in the western mountains has not resulted in appreciable disturbance of the water-regime. If there has been a little erosion for a year or two in some cases, it has been limited to the brief period while vegetation of one kind or another clothed the denuded spots. On the other hand, as the authors point out and illustrate, the removal of part of the timber may actually increase water-yields.

The showing which has been obtained by the Rocky Mountain Forest Experiment Station that thinning of the forest increases the storage of snow and the yield of water constitutes an example of mutual benefit both in production of timber and in water-yield. Some of the work which that Station has done along with the results which Church has obtained in the Tahoe-Mt. Rose Region and my own findings on the west slope of the Sierra Nevada, suggest that groupwise clear cuttings of a width equal to or a little greater than the height of the trees may be still more effective than a uniform thinning in trapping snow and doubtless also rain and thus contributing to a maximum yield of water. If the group-cuttings were numerous and more or less circular, the forest might be converted to something analogous to a honeycomb where the accumulation of snow and rain in the cells would be a maximum and the loss by evaporation would be a minimum owing to the shading by the intercellular screens of standing trees. Melting of snow would also be retarded.

The authors limit their subject to forested lands but they are surely aware that the problems and conflicts of multiple use involving protection of the water-users' interests are much more acute on the range-lands which constitute large parts of the drainage-areas where conservation of water is most urgent. Again it is doubtless possible by proper range-management to reduce surface runoff and erosion to a point where the long-time interests of the stock grower and the water-user would be reconciled. But the necessary reductions in the number of animals grazed per unit of area are not made voluntarily and public regulation of the numbers on public lands or by public acquisition of private lands is looked upon with disfavor if not with hostility by the livestock industry. The rapid silting of many of the reservoirs in the Rocky Mountain Region is, in my opinion, direct evidence of the fact that the water-users' interests have not received their share of consideration in the use of range-lands. This is a problem of reconciliation of interests which seems to me far more serious than that of timber-cutting in forested areas.

Finally a plea is made for a better understanding of mutual problems and objectives by water-users and foresters. Nothing is said of a highly important intermediary in this relation, namely, the water company which provides for the supply and distribution of the water to the consumers and represents their interests, usually with great efficiency. These companies, many of them publicly owned and operated, have a keen understanding and positive interest in the factors including vegetation which affect their water-supplies. They have been ready to cooperate with foresters and have sometimes taken the lead in forestry matters on their watersheds: Witness the efforts of water companies in Southern California in behalf of fire protection, the forestry activities of the city of Seattle on the Cedar River Watershed including acquisition, planting, protection, and sanitary regulations in connection with logging operations, and the extensive forest plantings, recently supplemented by other conservation activities in cooperation with the United States Soil Conservation Service, of the Utility District supplying water to communities east of San Francisco Bay. These and many other examples do not indicate any lack of understanding of objectives by the representatives of the water-users.

AFTERNOON SESSION

The second session of the South Pacific Meeting, American Geophysical Union, Section of Hydrology, was called to order by CHARLES PETIT, Soil Conservation Service, United States Department of Agriculture, who acted as Chairman.

LAND-USE AND VEGETATIVE COVER AS FACTORS INFLUENCING RUNOFF

Karl O. Kohler, Jr.

The estimating of intensity of runoff and of watershed-yield has long been an important problem to all engineers dealing with watershed-analyses. Many methods have been devised for making such estimates and, in California, as in other Western States, engineers are using various formulas and procedures for the evaluation of these hydrologic problems.

Regardless of the methods used, certain influencing factors are usually considered in each analysis. The slope of watershed, topography, conditions of sub-surface rock, shape and drainage-pattern, temperatures, intensity, and duration of precipitation, snow-conditions, soils and their condition, vegetative cover, and land-use are all factors that will influence the dispersal of precipitation through infiltration, and surface runoff. The effects of transpiration and evaporation are of minor importance in this connection.

Slopes and topography may be altered some by man, but are usually considered in their natural condition. The shape and drainage-pattern are usually fixed, but on smaller watersheds may be changed drastically by internal structural developments. Air-temperatures, conditions of subsurface rock, and precipitation are relatively constant. Snow-accumulations and melting-rates are frequently influenced by changes in watershed-conditions. Cover and use of watershed are to a large degree under the control of man and can be changed in a relatively short time from one extreme of good protection of cover and ground to the other extreme of poor protection of cover and little watershed. Conditions of soils and soil may similarly be affected by the use of the land in the watershed.

These runoff-factors are evaluated in formulas in various ways and differing combinations when the hydrologic characteristics of a watershed are analyzed. In the discharge-type formulas such as Kuichling's of $Q = A\{[44{,}000/(A + 170)] + 20\}$ and Cooley's of $Q = 200A^{2/3}$, there is only one variable--the area of the watershed and the remaining influencing factors are evaluated in the numerical components of the formula. A rainfall-factor, P, and a watershed-width ratio, W, are the variable factors used in Pettis' flood-flow formula $Q = 328PW^{5/4}$. The rational method of runoff-determination $Q = CIA$ adds to the area-factor a rainfall-runoff ratio C, and the rainfall-intensity I, during the period of concentration. Slope is added to the runoff-coefficients and rainfall-intensities in formulas such as the Burkli-Zeigler and MacMaths. The temperature-factor is applied by Grunsky and others and snow-melt is considered in some of the methods. H. L. Cook [see 1 of "References" at end of paper] uses physical characteristic groupings which include an analysis of the topography, soils, vegetative cover, and surface storage-capacity in conjunction with his flood-curves for flood-runoff estimation.

Considering that the factors of vegetative cover and watershed-use are important in the interpretation of the hydrology of a watershed and that, to a large degree, they can be controlled by man, I would like to present some information accumulated during the past few years about the influence of these conditions on watershed-runoff.

The effects of a watershed's protective vegetative cover on runoff will be reflected through the establishment of conditions conducive to higher rates of infiltration, and an increase in transpiration and evaporation. The land-use measures will determine to a large degree the amount of vegetative cover on the area and the other practices that will exert a retarding effect on the runoff of precipitation falling on the watershed.

Rainfall intercepted by trees or other heavy foliage is retarded in its movement to the soil, and that remaining on the leaves and branches is lost by evaporation. In heavy rains, this interception will probably have little effect on runoff; it is, however, a delaying influence that increases in importance as the precipitation decreases in amount.

Without considering the influence of a snow-cover on the ground, runoff will occur when the rate of precipitation exceeds the rate of infiltration and absorption. Any condition that will influence the rate of infiltration should influence the relationship between precipitation and runoff.

Plant-litter tends to break up the rain-drops, protects the soil from puddling, and holds water on the ground-surface for a longer period of time. The resulting dispersement of precipitation, its retarded flow to the soil, and the longer contact with the ground-surface, normally increase the amount of infiltration into the soil. Plant-cover affords a natural obstruction to the surface movement of the water and a well-developed root-system results in a more porous condition of the soil. A study [2] was made by the Soil Conservation Service at Ithaca, New York, between March 1 and 9, 1936, of the relative surface-water losses from a potato field with a slope of 14 per cent, a grass-pasture with a slope of 20 per cent, and a forested area with a slope of 27 per cent. The measurements of runoff resulting from 9.47 inches of rain and snowfall on these watersheds, during this period, showed that 88 per cent of the precipitation ran off the potato field, while only 0.2 per cent ran off the grassed area, and 0.5 per cent came from the forested area.

Overgrazing with its resulting reduction of plant-cover and increase in trampling with resulting soil-puddling, can seriously alter the runoff-characteristics of a watershed. This is indicated in a bulletin [3] by REED BAILEY on the violent floods that occurred in northern Utah in 1923 and 1930, in which he stated: "The three most plausible among the possible causes of the recent accelerated erosion and floods would doubtless be conceded to be (1) diastrophism as it might influence the gradient of the stream, (2) climatic change, involving greater or more intensive rainfall, and (3) destruction of the plant-cover with concomitant losses of surface-litter, reduction of humus content, modification of the physical properties of the surface soil, and a consequent increase in runoff and decrease in moisture-absorption on the watershed."

Mr. Bailey also stated in his conclusions: "It is concluded upon the evidence found on the watersheds that the floods, which caused the recent radical departure from the normal post-Bonneville erosion and sedimentation in the canyons of the Centerville-Farmington area, are directly attributable to the destruction, by overgrazing and fire, of the major portion of the vegetation and the concomitant loss of the plant-litter and more porous top-soil on critical parts of the watershed. There the soil and vegetation which had become established long ago and had been maintained through thousands of years, had been, until recently, the means of controlling runoff and preventing serious erosion."

Similar evidence is presented in a report made by the Inter-Mountain Forest and Range Experiment Station of the Forest Service, Ogden, Utah. The report [4] includes 15 years' measurements of precipitation and runoff from two watersheds in the mountain-range area in central Utah where the density of the herbacious vegetation on the watersheds was controlled by grazing. One watershed was grazed in a manner to maintain a plant-cover on approximately 40 per cent of the ground-surface during the 15-year period. The other watershed was grazed to maintain a cover of 16 per cent for the first five years; then it was ungrazed for five years, during which time the percentage of plant-cover increased from 16 to 40 per cent, and during the last five-year period light grazing was carried on to maintain the cover of 40 per cent.

During the first six years of measurements, the first, or controlled watershed had an average runoff of 2.52 per cent of the precipitation, while the second watershed had an average surface runoff of 10.33 per cent of the precipitation. During the next three years, the runoff from the controlled watershed averaged 3.03 per cent of the precipitation, while on the second watershed it amounted to 8.74 per cent. Measurements during the last five years of the experiment, when the percentage of plant-cover was about the same on both watersheds, showed runoff of 5.23 per cent on the first watershed and 5.49 per cent on the second watershed.

The effects of intense rainfall on watersheds denuded by brush-fires are well known in California. The runoff from the Verdugo and Arroyo Seco watersheds in Los Angeles County was measured during the winter of 1933-34, when the Verdugo Watershed had 33 per cent of its area burned off and the Arroyo Seco had only 0.6 per cent of its watershed without a vegetative cover. A total of about twelve and a half inches of precipitation produced a peak-runoff from the Verdugo Watershed at a rate of 1000 second-feet per square mile, while the Arroyo Seco discharged at a maximum rate of only 58 second-feet per square mile. The Verdugo flood included a debris-load that was discharged at a rate of about 50,000 cubic yards a square mile for the storm, but no measurable debris was discharged from the Arroyo Seco.

Land-use practices that protect farm lands during the runoff-season can effect a material reduction in the runoff and erosion from such lands. Contour-tillage, crop-rotations, contour-furrowing, listing, strip-cropping, green manures, cover-crops, level terracing, and similar practices are established to utilize the precipitation better in the area upon which it falls.

Contour-cultivation has shown a reduction of as much as 80 per cent of the runoff from rains of low and medium intensity as compared to that on similar fields cultivated up and down the slope. Crop-rotations develop conditions of soil favorable to rapid infiltration and, when compared to continuous row-cropping on experimental plots, have shown a reduction of more than 50 per cent in the runoff, though a somewhat lower figure is considered more applicable to general farming practice. Mechanical surface storage-capacities are measurable on areas that are contour-furrowed, listed, or level terraced.

An evaluation of the effects of proper land-use and watershed-management on the reduction of flood-runoff and erosion has been made in several flood-control surveys in California during the past few years by the United States Department of Agriculture. The first survey [5] was made on the Los Angeles River Watershed in Los Angeles during 1938 and 1939. The watershed-area contains about 537,000 acres of which 233,000 are rough, broken land supporting a cover of brush and woodland. About 116,000 are agricultural and grazing lands. The flood-waters generally originate as a result of local storms of high intensity and carry heavy debris-loads from the upper watersheds onto the lowlying agricultural, urban, and suburban areas.

The land-use measures recommended for the areas of brush and woodland include fire-control, improvement of vegetative cover, road-improvement to reduce bank-erosion and improvement of upper channels. Considering the rough topography, shallow soils, and storm-intensities, it was anticipated that the value of the recommended practices would be reflected primarily in a reduction of debris, and that a reduction of the capital peak-flow would occur mainly on those parts of the watershed where conditions were favorable for increased infiltration of the precipitation into the soils. A reduction in peak-runoff of 5 per cent was estimated for two mountain watersheds with a combined area of about 48,000 acres, and a general reduction of total runoff was estimated for the six mountain flood-source areas. It was estimated that the fire-control program alone would reduce the erosion-rate on the mountain slopes and the resulting debris-load 60 per cent below the present rate.

The survey also indicated that 87 per cent of the agricultural land would require remedial land-use measures to effect a reduction of runoff and debris-movement on the watershed. These measures would include winter cover-crops, crop-rotations, changes in cultural practices,

terracing, listing, and a range-improvement program. The estimated effectiveness of five of these more general practices is indicated in Table L-5 taken from the report

Table L-5

Treatment	Reduction of total runoff	Reduction of soil-loss
	pct	pct
Winter cover-crop	50	85
Organic matter incorporation	30	50
Permanent cover-crops	60	95
Contour-tillage	5	50
Crop-rotation	2	10

Wherever agricultural land-treatment was thought to be a factor in the designed storm-discharge, a basic reduction in runoff was computed for each subwatershed area.

A similar survey was made on the Santa Ynez River in Santa Barbara County in 1942 [6]. This watershed of about 576,000 acres has approximately 65,000 acres of cultivated lands, 210,000 acres of grazing land, and virtually all of the remaining acreage in brush and woodland. Floods usually result from winter rainstorms of high intensity.

About 45 per cent of the cultivated lands were believed to contribute significantly to the flood-damage in the watershed. The land-use measures recommended for the reduction of flood-peak flows and debris-movement include the conversion of some crop-lands to pastures, changes in cultural practices, crop-rotations, cover-crops, and minor structural work.

In order to correct the present problems of soil-compaction and local overuse on grazing land, an improvement and grazing-management program was proposed requiring fencing, stock-water developments, and regulated grazing.

The management program for the areas of brush and woodland would include fire-control and cover-improvement.

It is estimated that, if the complete proposed land-use program could be installed on the Santa Ynez Watershed, it would result in a reduction of flood-peaks varying from 18 per cent for floods of about 100,000 cubic feet per second to a reduction of 28 per cent for moderate floods of approximately 25,000 cubic feet per second. It was also anticipated that smaller flood-flows would be diminished by proportionately greater amounts.

The Russian River Watershed in Sonoma, Mendocino, and Lake counties, containing approximately 965,000 acres, was investigated in 1942 [7]. The watershed-area includes about 187,000 acres of cultivated and urban area, 184,000 acres of grass-woodland, 319,000 acres of mixed grass, brush, and woodland, 146,000 acres of brush-chaparral, and 129,000 acres of forest. Snowfall is insignificant in the watershed, and floods are produced by intense prolonged rainfall.

From a study of conditions of the watershed, it appeared that an improved vegetative cover on the watershed would result in a material reduction of flood-peaks. The land-use program recommended by the Department of Agriculture to attain the required protective cover would include practices similar to those recommended in the two previously mentioned flood-control reports. These practices would be applied primarily to critical eroding areas on about 45 per cent of the cultivated lands and 68 per cent of the grass-woodland areas, although it was assumed all of the lands in these classifications should use a satisfactory land-use program. The measures for the woodland-brush-grasslands and the brush-chaparral areas would be applicable to the entire acreage within these classifications. The forested area was believed to be in good condition, requiring no remedial measures other than fire-protection.

Assuming application of 100 per cent of the proposed land-use program on the watershed, it was estimated that flood-peaks could be reduced through a range from about 20 per cent for a flood of 62,000 second-feet to 50 per cent for a flood-peak of about 5,000 second-feet. This lowering in flood-peaks would be accompanied by a reduction of about 80 per cent of the soil-loss that was resulting in harmful deposition on the lower parts of the watershed.

Discharge-type runoff-formulas were not used in evaluating the effect of land-use practices and vegetative cover on runoff and erosion in these flood-control surveys. Basically, the estimates

were obtained from a comparative analysis of the present physical conditions of the critical flood-producing areas in the watersheds and the anticipated conditions after the land-use program had been effectively installed. Experiment-station data were used in the comparison where actual measurements of runoff, under different vegetative cover, soils, cultural practices, slopes, and other variable conditions of watershed, had been made. Because no measurements of this character had been made within the watersheds under study, or under exactly comparable conditions, existing data had to be adapted to local conditions. The possibilities for error in adapting these data obtained under markedly different conditions to those prevailing locally were recognized. As a check against the assumptions as to amount of runoff under different cover, topography, and conditions of land-use, a considerable number of infiltrometer-tests were made to assist in an evaluation of the assumptions arrived at on the basis of experimental data from other sections of the country. These tests also indicated the rather delicate balance between infiltration-capacity and precipitation-intensity which can be altered appreciably by changes in surface conditions.

Changeable conditions of surface of a watershed should be interpretable in discharge-formulas that include watershed-characteristic factors. The factors would indicate the degree of influence that vegetative cover and land-use would have on the intensity of runoff. Without a controlled watershed-management program, however, extreme caution would have to be used with these formulas when estimating capacities of critical structures.

During the past few years, the importance of watershed-use has become quite apparent to many people, especially in those locations where devastating floods, often carrying heavy debris-loads, have caused serious damage to the lowlying watershed-areas. Just as serious, but often not as apparent to the public, is the changing conditions of runoff on large agricultural, range, and forested areas throughout the country, caused by improper land-use practices.

Watershed-control is to a large degree in the hands of man and the public is awakening to the need for protective measures to minimize flood-damage as much as possible. Such a control can be attained only by the unified action of all people on the watershed. As watershed-management becomes more of a reality, there will be an increasing recognition given to the importance of evaluating the factors of vegetative cover and land-use in the hydrologic analyses of watersheds.

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DISCUSSION

B. A. MADSON (University of California, Davis, California)--There is little to be said regarding the paper just given. The writer has presented a general picture of the effects of cover and, as he indicates, such effect is complicated by other factors. He has selected random data to support his thesis as a basis for his land-use recommendation. His references, to say the least, were not well chosen as their interpretation has in some cases been subject to considerable controversy.

When intensity of rainfall is in excess of infiltration, runoff will occur. It is well recognized that a vegetative cover will check surface movement of water, and also protect the soil against the beating action of the rain and reduce erosion. To compare the runoff and erosion from a grass-covered area with that from a cultivated area (potato land in this case) and attribute the difference to the vegetative cover is hardly tenable. The modification of a soil incident to cultivation may greatly change its permeability and erosiveness. Here in California we fallow a good deal of land and in many cases have greatly increased runoff because of a dense plowsole formed by cultivation

which greatly reduces penetration. Under such conditions erosion is inevitable.

On the other hand, we have other fallow areas where plowsole formation has been prevented and where the soil has been kept loose and open mechanically, where runoff and erosion are actually less than when the land carried a natural vegetative cover.

I would also like to point out that vegetative covers vary greatly in their effectiveness in reducing erosion. A grass-cover is generally recognized as the most effective because, forming a mat on the surface of the soil, it is efficient in reducing the velocity of surface movement and protects the soil against the beating action of the rain. In the Watsonville Area, on a sandy soil, a good cover-crop of sour clover gave practically no protection against erosion. The plants of the sour clover are slender and stemmy, and the water and sand moved almost as freely between the stems as if the crop had not been present. A good grass-cover, on the other hand, with its rosette of leaves lying on the surface of the ground, afforded almost complete protection.

With the normal variability in topography and soil, it is difficult to set up comparable plots and attribute the difference observed to a single factor such as cover. Probably the most accurate results would be obtained on the same area with and without cover, which would, however, require many years to yield results of value.

Mr. Kohler's paper contains no new or original information on the subject of runoff or erosion. His data have obviously been selected to support his proposed land-use program.

NIEL F. MEADOWCROFT (Federal Power Commission, San Francisco, California)--In 1940 Robert H. Griffin and I, both at that time with the United States Forest Service, made a theoretical study of the Lone Pine Canyon Watershed in southern California, paralleling Lytle Creek which was referred to in Mr. Stafford's discussion this morning. The Lone Pine Watershed of about 15 square miles was burned in August, 1940, to the extent of about 70 per cent of its area. We made an analysis to determine the potential flood under that condition compared to the normal, assuming a maximum intensity of rainfall of six inches per hour for about 15 minutes and the same general storm-pattern as the flood of 1938 in southern California. The method of analysis was the same as that used by the Army Engineers for that area. As I remember the results of our study, the peak-discharge was increased about ten per cent and the maximum 24-hour discharge was increased about 25 per cent over the estimated corresponding flows from a normal watershed. Similar though lesser increases were determined for a storm of the magnitude of that of 1938. The results tend to confirm the observations made in the author's paper relative to the influence of vegetative cover.

ADDITIONAL ARGUMENTS FOR MODIFICATION OF THE RATIONAL FORMULA FOR RUNOFF FROM SMALL AGRICULTURAL AREAS

(Paper No. 2146, Scientific Journal Series, Minnesota Agricultural Experimental Station)

Charles G. Snyder

The "rational formula" for runoff

$$q = CIA \qquad (1)$$

assumes that q, representing only the maximum rate of runoff in cubic feet per second, varies jointly as the first power of I, the rainfall-intensity in inches per hour for the period of concentration, and A the area of the watershed in acres. Therefore, present use of the runoff-coefficient C infers that it represents the effect of topography, whether rolling or hilly, and the effect of vegetal cover, whether cultivated, pastured, or wooded, only on the maximum rate of runoff.

It is reasonable to expect that q may vary jointly as some power of A and I other than unity, giving a formula of the form

$$q = CI^xA^y \qquad (2)$$

Different types of vegetal cover directly affect runoff only when the amount of water held by canopy-interception and surface detention is still capable of increase. Therefore, the influence of cover on rates of runoff is negligible under conditions conducive to maximum rates of runoff which are well known to occur only when the surface has become virtually saturated. An indirect effect is exerted by variations of cover only as they influence rates of infiltration and time of concentration.

Table 1--Characteristics of watersheds used in developing the Roe-Snyder formula

Watershed No.	Area A	Average slope[a]	Approximate area in			
			Woods	Pasture meadow	Culti-vation	Other uses
	acres	pct	pct	pct	pct	pct
Jackson 4	15.7	5.44	39	..	..	..
Jackson 1	20.7	4.89	14	..	..	..
Jackson 3	49.2	3.99	25	..	..	..
Coshocton 177-1940	75.6	15.7	11	36	42	11
Jackson 5	112.0	2.74	24	..	..	..
Coshocton 10-1939	122	....	24	20	47	9
Coshocton 10-1940	122	....	25	48	21	6
Coshocton 196-1939	303	14.0	26	20	45	9
Coshocton 196-1940	303	14.0	26	44	22	8
Coshocton 20-1939	373	....	19	33	39	9
Coshocton 20-1940	373	....	22	57	18	3

[a] Average slope for the Jackson watersheds is the average drop from the farthest point to the gaging-station; average slope for the Coshocton watersheds is the product of the length of the contour in feet and the contour-interval in feet, divided by the area in square feet.

Because evaluation of the physical characteristics of a watershed in terms of a runoff-coefficient resulted in widespread opinions even among engineers with considerable experience, the studies herein reported were made in an effort to limit the determination for any given case of the coefficient C to more definite factors usually subject to fairly exact measurement.

In 1935 H. B ROE made a statistical analysis of the storm-data from three of the seven watersheds on the Murchison farm near Jackson, Tennessee, presented by C. E. RAMSER [see 1 of "References" at end of paper]. These watersheds are hereinafter referred to as the Jackson watersheds. In his analysis Roe further assumed that the slope, s, of the watershed should be included as a variable, the formula taking the general form

$$q = CI^x A^y S^z \tag{3}$$

The completed analysis evaluated the formula more exactly as follows:

$$q = 0.324\, I^{1.158}\, A^{1.037}\, S^{0.00} \tag{4}$$

which simplifies to read

$$q = 0.324\, I^{1.158}\, A^{1.037} \tag{5}$$

This formula, hereinafter called the Roe formula, has an advantage over the "rational formula" in that the indefinite coefficient C has been replaced by a constant value for all cases, but it also has certain limitations. It is applicable only to average agricultural watersheds of limited size whose topography and soils are similar to those on the Jackson watersheds.

Although the formula is based on very meager data it seems to establish two pertinent facts: (a) That the slope, s, does not enter the problem as a variable influencing the value of the runoff-coefficient; (b) that there is some merit to the assumption that q varies jointly as some power of I and A other than unity.

A similar graphical analysis was made by Roe and Snyder [2] of the data from four of the Jackson group supplemented by data from four of the subwatersheds of the North Appalachian Experimental Watershed, near Coshocton in central Ohio, as reported in Hydrologic Bulletins No. 1 for 1939 and No. 4 for 1940, of the Hydrologic Division of the Office of Research, Soil Conservation Service, United States Department of Agriculture, and hereinafter referred to as the Coshocton watersheds.

Excepting one loam-soil the soils of the watersheds studied fall into one broad textural class, namely, silt-loam. The average slopes of the watersheds varied from 2.74 to 15.7 per cent. The vegetal cover had known variations consisting of woodland from 11 to 39 per cent, of pasture or meadow from 20 to 48 per cent, and of cultivated areas from 18 to 47 per cent of the individual watershed-areas. Each watershed was made up of more than one type of cover (see Table 1).

For the Jackson watersheds, Ramser's report furnished all the values of q, I, and A. For the Coshocton watersheds the values of q and A were obtained directly from the report, but the value of I was determined for each storm by platting the runoff-hydrograph and superimposing rainfall-intensities from the data furnished. The time of concentration for the watershed was taken as the period of rise on the hydrograph and an equal time-period of intense rainfall previous to the runoff-peak was used to calculate the average rainfall-intensity.

Figure 1 [from 2] containing the hydrograph and rainfall-intensity record for the storm of June 11, 1940, on Coshocton Watershed 10, illustrates the method of determining I. The runoff began to concentrate rapidly at $13^h\ 10^m$, reaching its peak at $14^h\ 08^m$, making the period of concentration of runoff 58 minutes. An equal period of the most intense rainfall preceding the peak-runoff began at $12^h\ 45^m$ and ended at $13^h\ 43^m$, the weighted average for the period being 0.87 inch per hour, which is the value of I used for the given storm.

The values of q, A, and I as taken from the reports, or as separately determined and used in the analysis, are shown in Table 2 [Table 1 of 2].

The relation between q and I was determined by plotting on double logarithmic-graph paper the observed values of q from Table 2 against the corresponding calculated values of I. The data for each watershed show a definite tendency to form four groups which could be represented by regression-lines having constant-slope relationship but a distinct intercept-value at unit I for each watershed in each group. A review of the data showed that corresponding groupirgs on the separate watersheds were marked by a similarity in intensity- and time-characteristics of the storms. These groups were roughly outlined, in the article cited, as follows:

"Group I: Low intensities (for the most part appreciably less than 0.5 inch per hour average 0.27 inch per hour); long storms (average 114.5 minutes, the majority well in excess of one hour); areas of watershed, 75 to 373 acres.

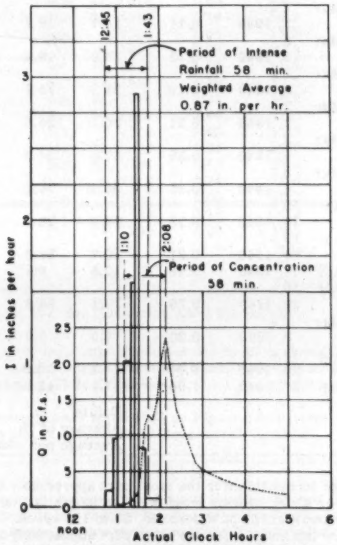

Fig. 1--Hydrograph and rain-intensity graph for storm of June 11, 1940, Coshocton Watershed No. 10

Table 2--Details of original data and corresponding determined and calculated items
(In development of Roe-Snyder formula for runoff)

Watershed[2] No. and area in acres	Storm No.	Storm Date	Determined value of I	Values of q Calculated	Values of q Observed	Variation of observed from calculated q Actual +	Actual −	Per cent +	Per cent −
Group No. 1 (C = 0.60, x = 1.14)									
C 20, 373	1	Feb 15, 1939	0.23	41.8	45.0	3.2	...	7.7	...
	6	Jul 8, 1939	0.44	87.7	63.0	...	24.7	...	28.2
	9	Jan 14, 1940	0.16	27.7	16.3	...	11.4	...	41.2
	10	Feb 10, 1940	0.15	25.7	30.6	4.9	...	19.0	...
	11	Mar 2, 1940	0.10	16.1	15.0	...	1.1	...	6.9
	12	Mar 2, 1940	0.12	19.9	23.0	3.1	...	15.6	...
	13	Mar 2 - 3, 1940	0.15	25.9	49.9	24.2	...	93.2	...
	14	Mar 30, 1940	0.12	19.9	13.9	...	6.0	...	30.1
	15	Apr 11 - 12, 1940	0.18	31.8	41.4	9.6	...	30.2	...
	16	Apr 19 - 20, 1940	0.20	35.8	75.5	39.7	...	111.0	...
	17	Apr 20, 1940	0.28	52.3	49.9	...	2.4	...	4.6
	26	Jun 28, 1940	1.20	275.5	208.0	...	67.5	...	24.5
C 196, 303	2	Feb 14 - 15, 1939	0.25	37.5	28.6	...	8.9	...	23.7
	3	Feb 14 - 15, 1939	0.25	37.5	28.6	...	8.9	...	23.7
	15	Jan 14, 1940	0.16	22.6	14.0	...	8.6	...	38.0
	16	Mar 2 - 3, 1940	0.11	14.7	16.2	1.5	...	10.4	...
	17	Mar 2 - 3, 1940	0.12	16.2	19.8	3.6	...	22.2	...
	18	Mar 2 - 3, 1940	0.18	25.8	25.7	...	0.1	...	0.4
	19	Mar 2 - 3, 1940	0.21	30.7	26.6	...	4.1	...	13.4
	20	Mar 3 - 4, 1940	0.25	37.5	24.0	...	13.5	...	36.0
	21	Mar 3 - 4, 1940	0.15	20.9	15.1	...	4.8	...	23.0
	23	Apr 19 - 20, 1940	0.23	34.0	26.2	...	7.8	...	22.9
	24	Apr 19 - 20, 1940	0.21	30.7	21.2	...	9.5	...	30.9
C 10, 122	2	Apr 11, 1940	0.18	10.8	8.5	...	1.7	...	15.7
	3	Apr 19 - 20, 1940	0.28	17.1	24.3	7.2	...	42.0	...
C 177, 75.6	1	Mar 2 - 3, 1940	0.20	7.3	7.3	0.0	0.0	0.0	0.0
	5	Apr 19 - 20, 1940	0.36	14.2	16.0	1.8	...	12.7	...
	12	Sep 27, 1940	1.04	47.4	41.8	...	5.6	...	11.8
				Totals				364.0	385.0
				Average of 28					374.5
				Average per cent					±13.4

"Group II: Moderate to high intensities (for the most part appreciably in excess of 1.5 inches per hour, average 2.28 inches per hour); storms from medium length to short (average 28 minutes, many running from 20 to 30 minutes); areas of watershed, 21 to 112 acres.

"Group III: Moderate to low intensities (for the most part appreciably less than one inch per hour, average 1.0 inch per hour); storms of moderate length (average 51 minutes, by far the greater number running well in excess of 30 minutes); areas of watershed, 75 to 373 acres.

Table 2--Details of original data and corresponding determined and calculated items (continued)

Watershed[a] No. and area in acres	Storm No.	Storm Date	Determined value of I	Values of q Calculated	Values of q Observed	Variation of observed from calculated q Actual +	Actual −	Per cent +	Per cent −
Group No. 2 (C = 0.36, x = 1.14)									
J 5, 112	1	Feb 19, 1918	1.41	59.6	68.0	8.4	...	14.1	...
	2	Apr 16, 1918	1.41	59.6	69.0	9.4	...	15.8	...
	4	Apr 28, 1918	2.05	91.4	90.0	...	1.4	...	1.5
	5	May 7, 1918	2.65	122.4	85.5	...	36.9	...	30.1
	6	May 12, 1918	1.31	54.8	39.4	...	15.4	...	28.1
	7	May 23, 1918	2.36	107.3	120.5	13.2	...	12.3	...
	8	Jun 1, 1918	2.08	92.9	70.0	...	22.9	...	24.7
	9	Jun 6, 1918	1.20	49.6	56.0	6.4	...	12.9	...
	10	Jun 6, 1918	1.20	49.6	66.0	16.4	...	33.1	...
	11	Jul 18, 1918	2.68	124.0	124.5	0.5	...	0.4	...
C 177, 75.6	3	Mar 3 - 4, 1940	0.40	9.6	7.9	...	1.7	...	17.7
	4	Apr 11, 1940	0.20	4.3	5.1	0.8	...	18.6	...
	6	Apr 19 - 20, 1940	0.32	7.4	7.9	0.5	...	6.8	...
	8	Jun 18, 1940	2.28	69.6	58.1	...	11.5	...	16.5
	10	Jun 28, 1940	1.83	54.2	50.0	...	4.2	...	7.7
J 3, 49.2	1	Feb 19, 1918	1.44	26.8	33.0	6.2	...	23.1	...
	2	Apr 16, 1918	2.04	39.9	42.5	2.6	...	6.5	...
	3	Apr 28, 1918	3.12	64.8	72.0	7.2	...	11.1	...
	4	May 7, 1918	3.24	67.6	58.0	...	9.6	...	14.2
	5	May 12, 1918	1.68	32.0	26.0	...	6.0	...	18.8
	6	May 23, 1918	2.76	56.3	68.0	11.7	...	20.8	...
	7	Jun 1, 1918	2.64	53.5	39.0	...	14.5	...	27.1
	8	Jun 6, 1918	2.04	39.9	42.5	2.6	...	6.5	...
	9	Jul 18, 1918	3.00	61.9	80.0	18.1	...	29.2	...
J 1, 20.7	1	Feb 19, 1918	2.40	20.3	20.0	...	0.3	...	1.5
	2	Apr 16, 1918	3.84	34.8	26.5	...	8.3	...	23.9
	3	Apr 28, 1918	4.44	41.0	38.0	...	3.0	...	7.3
	4	May 7, 1918	3.60	32.3	28.5	...	3.8	...	11.8
	5	May 12, 1918	1.92	15.8	16.5	0.7	...	4.4	...
	6	May 23, 1918	3.12	27.4	32.0	4.6	...	16.8	...
	7	Jun 1, 1918	3.24	28.6	24.5	...	4.1	...	14.3
	8	Jun 6, 1918	3.00	26.2	29.5	3.3	...	12.6	...
	9	Jun 6, 1918	2.28	19.2	20.0	0.8	...	4.2	...
	10	Jul 18, 1940	4.20	38.5	44.5	6.0	...	15.6	...
				Totals				264.8	245.2
				Average of 34				255.0	
				Average per cent				± 7.5	

[a]Watershed designation is C for Coshocton and J for Jackson.

"Group IV: Moderately high intensities (for the most part well in excess of one inch per hour, average 1.25 inches per hour); storms short and sharp (average 33.5 minutes, many under 25 minutes); areas of watershed, 75 to 373 acres."

The four groups were graphed separately in Figures 2-5 [from 2] which show the relationship existing between q and I and is described by the general equation

$$q = C_1 I^{1.14} \qquad (6)$$

To obtain the relationship between q and A for the four groups, the intercept-value of C_1 of each regression-line where it intersected the line representing I equal to unity, was plotted, on double logarithmic-graph paper, against the corresponding A-value of the watershed (see Fig. 6). The relationship thus obtained is expressed by the general equation

Table 2--Details of original data and corresponding determined and calculated items (continued)

Watershed[a] No. and area in acres	Storm No.	Storm Date	Determined value of I	Values of q Calculated	Values of q Observed	Variation of observed from calculated q Actual +	Actual −	Per cent +	Per cent −
		Group No. 3 (C = 0.22, x = 1.14)							
C 20 373	4	Jun 19, 1939	0.20	13.1	10.3	...	2.8	...	21.9
	5	Jul 8, 1939	0.87	70.0	75.3	5.3	...	7.6	...
	8	Jan 14, 1940	0.28	19.2	18.8	...	0.4	...	2.1
	20	May 24, 1940	0.20	13.1	11.2	...	1.9	...	14.5
	22	Jun 11, 1940	0.58	44.1	45.9	1.8	...	4.1	...
	23	Jun 18, 1940	1.58	138.3	121.0	...	17.3	...	12.5
	25	Jun 28, 1940	1.45	125.4	120.0	...	5.4	...	4.3
	27	Sep 27, 1940	1.04	85.9	100.0	14.1	...	16.4	...
C 196, 303	1	Feb 14 - 15, 1939	0.26	14.3	11.6	...	2.7	...	1.9
	4	Jun 18, 1939	0.60	37.3	25.5	...	11.8	...	31.6
	5	Jun 18, 1939	0.39	22.8	17.6	...	5.2	...	22.8
	6	Jun 18 - 19, 1939	0.51	30.9	30.9	0.0	0.0	0.0	0.0
	7	Jun 18 - 19, 1939	0.27	15.0	19.3	4.3	...	28.7	...
	9	Jul 8, 1939	1.52	107.5	62.1	...	45.4	...	42.2
	10	Jul 8, 1939	1.02	68.2	47.2	...	21.0	...	30.8
	14	Jan 14, 1940	0.32	18.1	17.6	...	0.5	...	2.8
	22	Mar 18, 1940	0.35	20.1	17.6	...	2.5	...	12.4
	29	Sep 27, 1940	0.76	48.8	39.3	...	9.5	...	19.4
	30	Sep 27, 1940	0.14	7.1	6.7	...	0.4	...	5.6
C 10, 122	1	Feb 15, 1939	0.28	6.3	9.4	3.1	...	49.2	...
	5	Jun 11, 1940	0.87	22.9	23.6	0.7	...	3.3	...
	6	Jun 18, 1940	1.82	53.0	45.3	...	7.7	...	14.5
	7	Jun 28, 1940	0.50	12.2	17.9	5.7	...	46.7	...
	9	Sep 30, 1940	0.42	10.0	9.8	...	0.2	...	2.0
C 177, 75.6	2	Mar 2 - 3, 1940	0.78	12.5	8.6	3.9	...	36.0	...
	7	Jun 10, 1940	1.69	30.2	14.1	16.1	...	53.3	...
	9	Jun 28, 1940	2.68	51.1	50.0	1.1	...	2.2	...
	11	Jul 23, 1940	2.83	54.3	44.6	10.3	...	19.0	...
J 4, 15.7	1	Feb 19, 1918	1.89	7.2	6.5	...	0.7	...	9.7
	2	Apr 16, 1918	2.92	11.9	13.5	1.6	...	13.4	...
	3	Apr 28, 1918	3.77	15.9	15.0	...	0.9	...	5.7
	4	May 7, 1918	3.51	14.6	15.5	0.9	...	6.2	...
	5	May 12, 1918	1.89	7.2	9.0	1.8	...	25.0	...
	6	May 23, 1918	2.83	11.5	15.5	4.0	...	34.8	...
	7	Jun 1, 1918	3.00	12.2	13.5	1.3	...	10.6	...
	8	Jun 6, 1918	2.14	8.3	9.5	1.2	...	14.5	...
	9	Jul 18, 1918	3.51	14.6	25.5	10.9	...	74.7	...
			Totals					335.2	367.2
			Average of 37					351.2	
			Average per cent variation						±9.5

[a]Watershed designation is C for Coshocton and J for Jackson.

$$C_1 = CA \qquad (7)$$

The value of C (its intercept-value when A equals unity) obtained from Figure 6 for each of the four groups and the resulting product CA substituted successively for its equivalent C_1 in equation (6) give the following results hereinafter called the Roe-Snyder formula as presented in [2].

Table 2--Details of original data and corresponding determined and calculated items (concluded)

Watershed[a] No. and area in acres	Storm No.	Storm Date	Determined value of I	Values of q Calculated	Values of q Observed	Variation of observed from calculated q Actual +	Actual −	Per cent +	Per cent −
Group No. 4 (C = 0.07, x = 1.14)									
C 20, 373	2	Jun 18, 1939	0.68	16.8	11.2	...	5.6	...	33.3
	3	Jun 19, 1939	0.33	7.4	7.8	0.4	...	5.4	...
	7	Oct 27, 1939	1.06	27.9	14.4	...	13.5	...	48.4
	19	May 24, 1940	0.33	7.4	6.0	...	1.4	...	18.9
	21	Jun 10, 1940	1.24	33.4	51.9	18.5	...	55.4	...
	24	Jun 23, 1940	0.72	17.9	26.1	8.2	...	45.8	...
C 196, 303	11	Oct 26, 1939	1.17	25.4	22.1	...	3.3	...	13.0
	12	Oct 27, 1939	0.90	18.8	32.6	13.8	...	73.4	...
	13	Oct 27, 1939	0.47	9.0	13.3	4.3	...	47.8	...
	25	Jun 12, 1940	1.50	33.7	20.2	...	13.5	...	40.1
	26	Jun 28, 1940	1.26	27.6	29.0	1.4	...	5.1	...
	27	Jun 28, 1940	1.56	35.2	41.5	6.3	...	17.9	...
	28	Jul 23, 1940	2.27	54.0	41.9	...	12.1	...	22.4
	31	Sep 27, 1940	1.83	42.2	42.7	0.5	...	1.2	...
C 10, 122	4	Jun 10, 1940	1.99	18.6	13.9	...	4.7	...	25.3
	8	Jul 8, 1939	2.37	22.7	29.8	7.1	...	31.3	...
	10	Oct 26, 1939	1.58	14.3	10.3	...	4.0	...	28.0
			Totals					283.3	229.4
			Average of 17						256.35
			Average variation						±15.1

[a]Watershed designation is C for Coshocton and J for Jackson.

$$\left.\begin{aligned} &\text{Group I, } q = 0.60AI^{1.14}; \text{ Group II, } q = 0.36AI^{1.14} \\ &\text{Group III, } q = 0.22AI^{1.14}; \text{ Group IV, } q = 0.07AI^{1.14} \end{aligned}\right\} \quad (8)$$

In these formulas the value of C is dependent only on the general characteristics of the storm and q varies jointly as the first power of A and the 1.14 power of I.

These values are not intended as final but are offered to define the trend until further research either confirms or denies them. Further refinements are needed in describing storm-types and in the method of determining the time of concentration of a watershed. A great mass of complete storm-data for many regions and classes of storm is necessary before final satisfactory improvements can be made.

Figure 7 may be of interest as showing a comparison of results obtained for different rates of rainfall calculated by the three general formulas discussed herein. It is evident that such a chart can cover only a limited specified condition. The one shown is believed to cover average conditions, obviously represented in the Roe-Snyder formula by Group II and in the "rational formula" by the value of C which is the average of the values suggested by RAMSER for the six classes of land described by him. This average C-value is 0.42. The resulting values of q for a given acreage as determined by the three formulas exhibit a greater spread as the value of I is increased. Furthermore, it is notable that the order of magnitudes reverses as larger intensities are used.

The data used in this analysis were obtained of soil, topography, cover-combinations, and storm-characteristics typical of the area drained by the upper Mississippi River System. The application of the Roe-Snyder formula in its present form is, therefore, assumed limited to these conditions and to areas from 15 to 400 acres in size.

A fair reliability seems indicated in the Roe-Snyder formulas by the fact that the average per cent variation of the observed from the calculated values (see Table 3) for the quite considerable

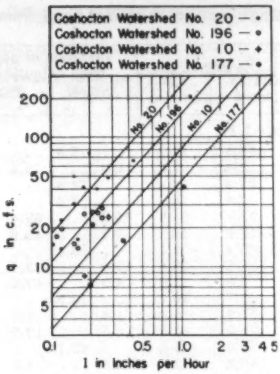

Fig. 2--Relation of q to I, Group I

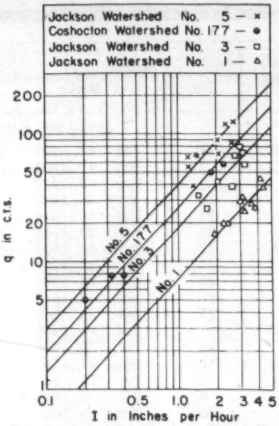

Fig. 3--Relation of q to I, Group II

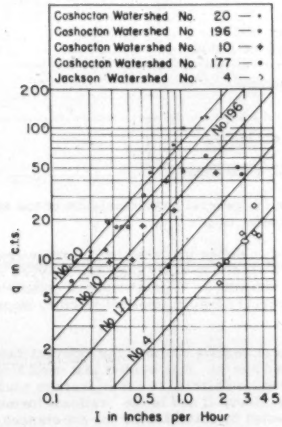

Fig. 4--Relation of q to I, Group III

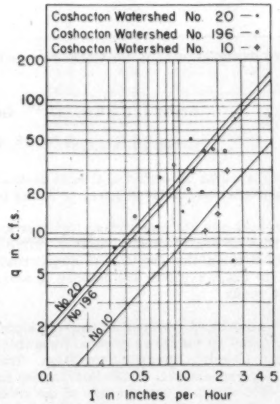

Fig. 5--Relation of q to I, Group IV

number of storms in each group is not excessively high as usually considered in engineering field-practice.

The marked uniformity of slope of the regression-lines showing the relationship between q and I, as well as between the q intercept-values and A, and the equally marked lack of any relationship between percentage of any type of vegetal cover and the q-value seems to the author to clearly justify the following conclusion.

The value of the runoff-coefficient is primarily dependent on the character of the storm producing the runoff. This value is independent of the slope of the watershed for the rolling agricultural land in this region.

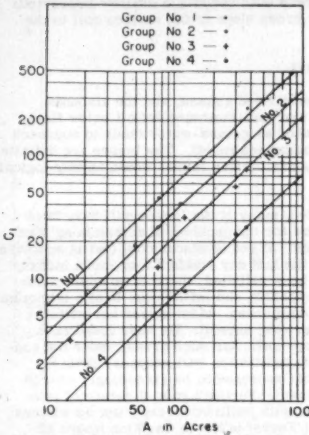

Fig. 6--Relation C to A (through values of C_1 in Figs. 2 to 5, when I equals unity)

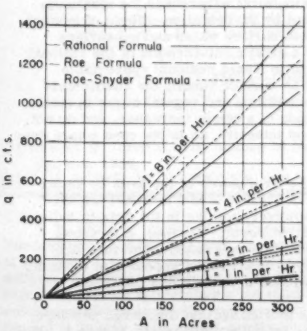

Fig. 7--Comparison of values of q by the Rational, Roe, and Roe-Snyder formulas for farm-areas of average character

Table 3--Average per cent variation of observed from calculated values of q in the four groups of storms used

Group No.	Number of storms	Average per cent variation
1	28	± 13.4
2	34	± 7.5
3	37	± 9.5
4	17	± 15.1

If the foregoing conclusion is justified, then, in determination of the required capacities of outlet-structures and waterways on the basis of an economic period, intensity-frequency data can serve to the fullest extent only if the expected frequency of a given rate of rainfall is known in conjunction with a definite type of storm.

References

[1] Runoff from small agricultural areas, J. Agric. Res., v. 34, May, 1927.

[2] A logical modification of the rational formula for runoff from small agricultural areas, Agric. Eng., v. 24, No. 12, December, 1943.

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DISCUSSION

A. F. PILLSBURY (University of California, Los Angeles, California)--The main objective of the author in presenting this paper would appear to be to reassert that the decrease in peak-flow of runoff as related to rainfall-intensity should be treated as a ratio of that intensity. I essentially agree with this approach to the problem of estimating peak-floods from small agricultural watersheds. Certain assumptions of the author, however, are open to question.

Most recent work on the relation of rainfall to runoff is based on the assumption that runoff equals rainfall minus losses. This is a reasonable approach to the problem of estimating total runoff. Rainfall can be considered to be disposed of as follows:

(1) Some is intercepted by vegetation before reaching the ground and is subsequently evaporated.

(2) Some is temporarily stored on the ground-surface, in stream-beds, in lakes, etc.; this portion eventually runs off or contributes to infiltration or evaporates directly.

(3) Some moves into the soil; this infiltration-portion is disposed of as follows: (a) It replenishes soil-moisture previously depleted by transpiration and evaporation; the soil may thus be brought up to field-capacity, and the moisture so held will be available for later transpiration and evaporation; (b) some moves downward to a water-table, and is lost from surface flow within the watershed; (c) some moves downward to a water-table, but reappears as surface flow within the

watershed; frequently, this portion moves vertically downward until striking a shallow impervious subsoil or bedrock, thence it moves more or less down the cross slope in the surface soil to the stream-channel.

(4) The balance moves off immediately as surface runoff.

On a seasonal or storm-basis, interception is a relatively fixed amount, and the amounts charged to transpiration and evaporation depend upon the prior soil-moisture deficit below field-capacity. The amount of moisture moving out of the watershed as ground-water tends to approach a fixed rate for the duration of each storm. The balance comprises runoff. The losses are definitely not a ratio, and the assumption that total runoff equals rainfall minus losses would appear logical in every way.

Under the conditions where major floods can be expected, many of the losses will have been completely satisfied, and a different approach may be needed for the problem of determining maximum rate of runoff. LYNCH has said [see 1 of "References" at end of discussion] that in southern California "A rainfall of eight inches in ten days, of which the last day yields 2.5 or more inches, results in heavy floods." In other words, interception has been satisfied, there is no appreciable evaporation or transpiration, all soil-moisture is at field-capacity, and infiltration is at a minimum just before the intense rainfall, which produces the flood, commences. Most upland agricultural soils in southern California have a shallow, relatively impervious, subsoil. We have found such subsoils with only six thousandths the permeability of the top-soil. For such areas, under the condition of prior wetting indicated by Lynch, practically all the infiltration will reappear down the watershed as surface runoff, and the stage will be set for that response to be exceedingly prompt because of the prior creation of a water-table above the subsoil. Further, rate of return of subsurface flow to the surface can often be expected to increase with infiltration-capacity, as witness the behavior of the watersheds of the Coweeta Experimental Forest in North Carolina where all rainfall of all intensities apparently moves into the soil, but almost immediately reappears as surface flow in the stream-channels [2].

Therefore, it is only reasonable that on many small agricultural watersheds the maximum rate of runoff approaches the rate of precipitation as modified by the detention-effects of surface storage and subsurface storage. The detention-effects on both surface water and subsurface water are essentially functions of the rainfall-intensity, and a coefficient-formula of the rational type is most applicable. However, where (as frequently found in humid regions) appreciable amounts of infiltration do not reappear within the watershed as surface runoff, the coefficient-formulas are of decreasing value. Then, the effects of soil-condition and vegetal cover in maintaining infiltration-capacity remain important as the magnitude of a storm increases, and do not diminish to negligible magnitude with increase in duration and intensity, as is the case where deep percolation is of minor importance.

The author's conclusion that discharge should vary as the first power of the area on small watersheds is sound. And, if the curves shown in the author's Figures 2 to 5 are correct, all other steps and conclusions follow of necessity. There is, however, nothing in the data to indicate that intensity should be evaluated at anything other than the first power. Further, it is shown above that a coefficient-formula is completely valid only on certain watersheds, and then only when certain conditions as to prior wetting have been satisfied. It would not appear that most of the storms used by the author were preceded by sufficient rainfall to satisfy this condition.

The data used by the author are simplified if intensity is plotted against discharge per acre. Then all watersheds are on a comparable basis. This is done on the accompanying Figure 1. The points so plotted do not justify any curves corresponding in slope to $I^{1.14}$, nor do they show justification for four distinct curves, even if curves for other than a maximum value of C were permissible. It can probably be assumed that the points closest to the 100 per cent runoff-rate line approach the requirements of prior wetting.

The location of a few of the points on this graph makes one of the following appear to be true: (a) Assumptions by which intensity is obtained are not valid; (b) the data are in error; (c) outside areas contribute to the runoff of some watersheds. Coshocton 20, where for one storm the rate of runoff equalled the intensity, is an example.

As stated by the author, these data are altogether inadequate to set up a general formula. But if one were set up it would probably be $Q = 0.54IA$. In any event, it is dangerous to use any formula without knowledge of the soils and geology of the watershed, and frequently vegetal cover and cultural practices are of importance.

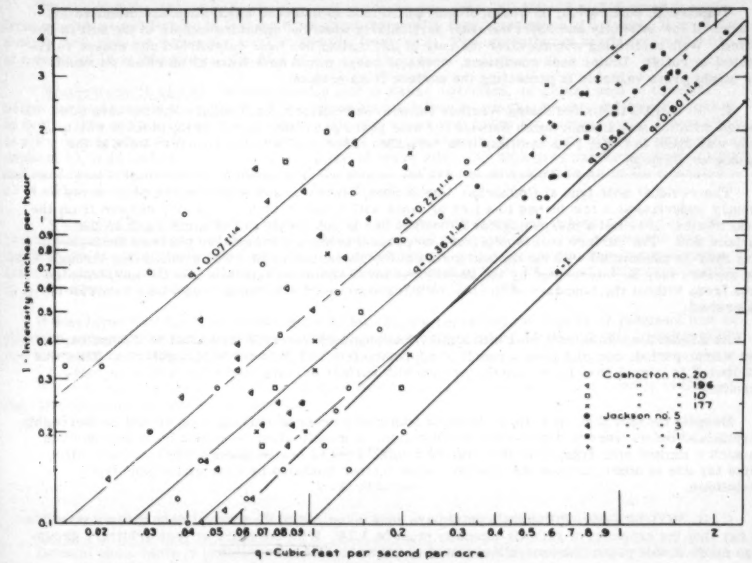

Fig. 1--Intensity versus discharge per acre

References

[1] HENRY B. LYNCH, The history of floods in southern California, Trans. Amer. Geophys. Union, pp. 6-8, 1939.

[2] C. R. HURSH, M. D. HOOVER, and P. W. FLETCHER, Studies in the balanced water-economy of experimental drainage-areas, Trans. Amer. Geophys. Union, pp. 509-517, 1942.

J. B. BROWN (Agricultural Extension Service, University of California, Berkeley, California)--For a storm of given intensity, the watershed-area has a receptive capacity dependent upon duration of the given intensity and the moisture-content and depth of the receptive soil. Gross reception is different for different intensities and for different moisture-conditions. As storms continue, the rate of reception approaches a constant for the given watershed. Any increase in intensity of a continuing storm above the rate necessary to maintain the rate of constant reception is totally reflected in runoff. The runoff-coefficient C must include consideration of length of storm and receptive capacity of watershed at time of storm.

In the development of the four formulas of this paper, storm-data from a number of the watersheds appear in more than one formula. In the case of Coshocton 20, the values of C are 0.07, 0.22, and 0.60, respectively. For a given watershed, the area is fixed and the power of the intensity is also a constant. The only variable is the coefficient C. Many of the intensities of the various storms used in determining the coefficients C are the same or nearly so for as many as three of the four different values of C set forth in this paper. In view of the above, the only conclusion that can be reached is that of the author that the value of the coefficient C is primarily dependent upon the characteristics of the storm producing the runoff. The selection of a coefficient for calculation of flow on another watershed would be extremely difficult. It would involve judgment based on wide experience and considerations of depth of soil-mantle, water-properties of the soil, and soil-moisture conditions previous to the storm.

Vegetation, cultivation, or works of man which tend to increase infiltration are effective in storms of low intensity and short duration particularly when the moisture-supply in the soil is depleted. With continuing storms after the rate of infiltration has been established any excess is reflected in runoff. Under such conditions, works or cover would have little or no effect on runoff but might prove valuable in protecting the surface from erosion.

R. W. GERDEL (United States Weather Bureau, Sacramento, California)--Having been connected with the Soil Conservation Service for nine years preceding July 1, 1943, most of which time was spent in Ohio, I am familiar with variables associated with the research work at the Coshocton Project.

The residual soil-type at Coshocton, like in many other parts of southeastern Ohio, is frequently underlaid at a few inches to a foot or more with a heavy, impervious clay derived from the local shales. It is not a morphological B-horizon and is not always in the same plane as the surface soil. The surface soil is dependent on present topographic features whereas the layer of clay may be associated with the dip and strike of the parent material. Water infiltering through the surface may be intercepted by the impervious layer and move laterally into the instrumented area from without the boundary of the plot or microwatershed even when it may be a headwater-watershed.

At Zanesville, Ohio, on a soil with similar pedologic characteristics to that at Coshocton, for one storm-period, one plot gave a runoff of approximately 140 per cent of precipitation. This was attributed to lateral flow from outside the plot with surface seepage occurring within the plot-boundary.

Despite the fact that the rational formula admittedly needs modifying, data should be thoroughly scrutinized before used to develop any modification. A modification developed from data derived on such a limited soil-type, characteristic of a small area of southeastern Ohio, may have little value for use in other parts of the country unless further modified by a factor for soil-type variations.

C. G. SNYDER--Mr. Pillsbury's points are well taken. With the present data it is not possible to say that the exponent of rainfall-intensity must be 1.14. With the more or less arbitrary groupings made in this paper the analysis resulted in this value.

I believe the groupings serve to bring out an important fact regarding economy of design based on the intensity for a given time-period of intense precipitation which may be expected to recur with a selected frequency. As pointed out, the runoff in the various groups is not so much dependent upon the intensity alone as upon the intensity in conjunction with definite storm-patterns which influence the moisture-conditions prevailing on the watershed at the time the intense rainfall starts. Therefore, intensity-frequency data would serve much better in predicting the probable frequency of overtaxing the designed capacity of a structure if the intensities were coupled with definite types of storm-patterns in determining frequencies from records of rainfall.

The point on the graph for the Coshocton 20 Watershed is a result of the method used in arriving at the time of concentration for the various storms. The rainfall-intensity of the storm in question was higher than 0.2 inch per hour just preceding the peak-runoff and at one point reached a maximum of 1.20 inches per hour for one minute.

In predicting maximum ratio of runoff from small areas a high degree of accuracy can only hope to be attained by thorough knowledge of all factors affecting runoff from these areas and the experience, essential as a guide, in interpreting this knowledge. The simple runoff-formulas are of value, however, in tempering the judgment of the inexperienced engineer likely to be involved in problems concerning these small areas.

With regard to the question raised by Mr. Gerdel, it should be noted that of the eight watersheds used, four were from Coshocton. The use of these watersheds was based on the descriptions of soil published in "Hydrologic data, North Appalachian Experiment Watershed, Coshocton, Ohio, 1939" by the Hydrologic Division, Office of Research, Soil Conservation Service, Hydrologic Bulletin No. 1, November 1941. A detailed description of the predominant soil-type on watershed No. 177 was not given, therefore the description of a bordering watershed of the same soil-type follows, along with the descriptions of watersheds Nos. 10, 20, and 196 quoted from the previously mentioned publication.

"Watershed No. 131--Predominating soil is Muskingum loam, an Upland soil derived largely from sandstone and lighter in texture throughout the profile than Muskingum silt-loam. It is rather shallow and contains numerous small sandstone fragments. The unweathered sandstone rock occurs at a depth of 18 to 30 inches." (P. 85.)

"Watersheds 10 and 20--Predominating soil is Keene silt-loam, an Upland soil of residual origin derived largely from shale. The surface soil is brown to grayish brown, six to eight inches in depth. The subsoil is reddish brown to yellowish brown just below the surface soil. The texture is silt-loam grading into silty clay-loam and then into heavy silty clay. Slight mottling begins at a depth of 12 to 24 inches, below which is a layer of heavy silty clay with gray predominating. Shale and sandstone fragments occur throughout the profile but are not so numerous as in the Coshocton or Muskingum soils. Drainage is fair." (Pp. 43 and 49.)

"Watershed No. 196--Predominating soil is Coshocton silt-loam, an Upland soil of residual origin derived from shale and sandstone. The surface soil is brown to grayish brown and has a depth of six to eight inches. The subsoil is reddish brown to yellowish brown, ranging in texture from silt-loam to silty clay-loam. Mottling begins at a depth of 24 to 36 inches. Drainage is fair to good. Shale and sandstone fragments occur in the profile." (P. 55.)

It was hoped that the observation made by Mr. Brown regarding the degree of judgment and experience necessary in the use of these formulas could be clarified by additional data on other soils and improved methods of grouping storms.

If a reasonable accuracy could be obtained from a formula based on factors readily evaluated the formula would be extremely valuable.

INFILTRATION AND THE PHYSICS OF SOIL-MOISTURE

L. K. Sherman

This is a study of infiltration in relation to capillary and noncapillary porosities.

Several basic facts of practical importance regarding infiltration-capacity curves have been determined or definitely indicated.

The data herein used consist of five infiltration-experiments, selected at random, from a record of 68 observations on different soils throughout the United States. These data are published by the United States Department of Agriculture [G. R FREE, G. M. BROWNING, and G. W. MUSGRAVE, Relative infiltration and related physical characteristics of certain soils, Tech. Bull. No. 729, July, 1940]. The experiments consisted of the application of infiltration-water, at capacity-rates, for a period of three hours. This was called the "initial run". After a lapse of 24 hours, another three-hour application of infiltration was made at capacity-rates. This was called the "wet run". Before each of the two runs a record of the existing percentages of soil-moisture was taken from the surface to a depth of 25 inches.

The data for the five sites used in this paper are shown in the accompanying Table 1 and Figures 1, 5, and 6. Based upon these data, the writer has derived the following:

(1) The rates and depth of penetration of applied infiltration into the soil-profile
(2) The mass-curves of the volume of infiltration appearing as capillary soil-moisture and the rates of this capillary absorption
(3) Mass-curves of noncapillary volumes of infiltration
(4) The f_c-curves of total infiltration, capillary absorption, and noncapillary infiltration
(5) The condition which causes an ultimate constant infiltration-capacity
(6) The soil-moisture phenomena during a short interval between rainfalls

Concept--The writer has found it useful to keep in mind the following concepts of infiltration, porosity, and moisture in the soil-profile. Consider a column of the soil of one square inch at the surface and extending down d inches into or through the zone of aeration. Assume that this soil has a noncapillary porosity of 30 per cent. The soil-column is thus penetrated by channels, capable of carrying gravity water, through the soil. These channels extend not only downward, but also laterally in all directions. These channels are constricted at numerous points, but infiltration-water finds its way downward through the lines of least resistance. In each cubic inch of soil,

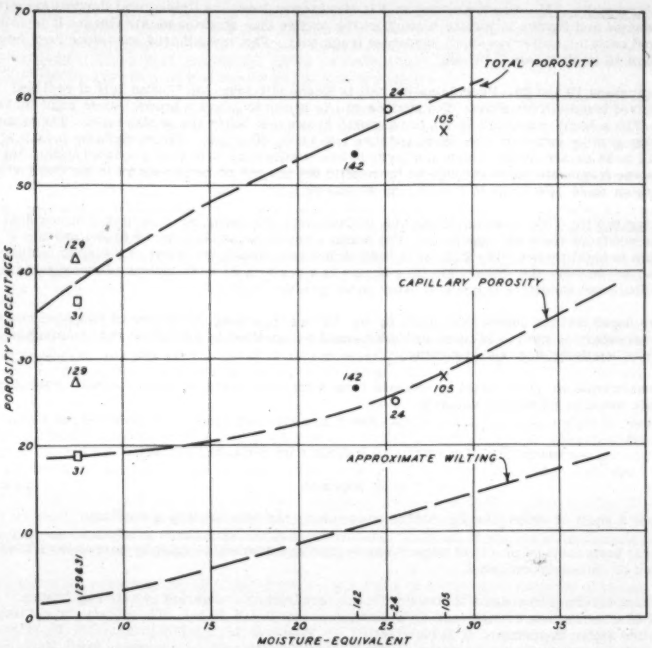

Fig. 1--Soil-porosity in percentages of soil-volume platted in order of soil-moisture equivalent (all data except wilting-point are from U.S. Dep. Agric. Tech. Bull. 729)

there is an average of 0.30 cubic inch of these noncapillary channels. If d = 20 inches, there would be capacity for six cubic inches of water.

The soil-column, which is penetrated by these larger gravity-water channels, is filled with small capillary pore-spaces. This capillary porosity of, say, 25 per cent, has a stronger avidity for water than for air. The force of capillarity acts in all directions and it frequently exceeds the force of gravity. Capillary water always moves from the wet spaces toward the drier spaces in accord with well-established laws relating to capillary potential.

In the surface layer, of about six inches, when the soil is dry, infiltration enters the soil not only through the larger gravity channels, but also through direct capillary action over the entire surface. This surface capillary movement decreases as the water penetrates deeper. The capillary potential declines so that capillary intake of surface water proceeds at a slower rate. The water in the gravity channels, however, continues to penetrate deeper and at a fairly uniform rate. This gravity water now furnishes a supply, at relatively high potential, for lateral capillary absorption into the soil. The gravity channels are the water-mains and the capillary pores are the local supply-feeders.

Suppose that infiltration has been furnished at capacity-rates for three hours and is then stopped. It is found that water has penetrated to a depth of 20 inches, then this condition exists: At the surface the soil has been subjected to a three-hour supply period for capillary absorption;

Table 1--Data used[a]

Site	Station, date, and detail	f_c	Run	Soil-moisture before run at depth of inches			Cumulative amounts of infiltration in minutes				
				0-7	7-15	15-25	15	30	60	120	180
				pct	pct	pct	in	in	in	in	in
31	Watkinsville, Georgia; peas, oats, cotton; April 25, 1938; rain-simulator	0.40	Initial	10.5	15.5	26.4	0.67	1.22	1.97	3.07	4.01
		...	Wet	14.0	18.6	26.8	0.20	0.37	0.66	1.09	1.49
129	Guthrie, Oklahoma; wheat; April 4, 1938; tube	0.53	Initial	10.6	13.5	15.3	1.02	1.46	1.21	3.56	4.83
			Wet	16.9	17.1	17.7	0.32	0.52	0.83	1.41	1.96
142	Dayton, Washington; wheat; June 2, 1938; tube	0.80	Initial	12.0	12.8	12.8	1.71	2.33	3.28	4.88	6.34
			Wet	27.3	24.5	22.2	0.75	1.18	1.73	2.63	3.45
105	Spring Valley, Minnesota; corn; September 17, 1937; tube	1.42	Initial	21.1	15.2	13.9	1.87	2.95	4.42	6.62	8.49
			Wet	32.7	27.4	23.9	0.76	1.18	1.97	3.46	4.88
24	Marcellus, New York; blue-grass; October 8, 1937; tube	(b)	Initial	14.6	15.4	14.3	4.70	7.71	12.11	18.82	24.58
			Wet	32.3	24.3	22.5	2.26	4.00	7.22	12.92	17.68

[a] See Figures 5 and 6 for data on porosity; all data from U. S. Dep. Agric. Tech. Bull. 729. [b] No f_c in 30 hours.

at depth of 20 inches the soil has just begun to have an additional supply of capillary moisture; at about ten inches, or mid-depth, the soil has had a one-and-one-half hour period for the supply of additional capillary moisture.

Though the supply of further infiltration was stopped at the end of three hours, the gravity channels are full of water. Capillary action continues to draw upon this gravity water until the capillary pores are all filled or until the gravity storage is gone.

A word here on the phenomena of f_c or ultimate constant of infiltration-capacity. Normally the soil just below the zone of aeration, or the root-zone, holds 100 per cent of water in its capillary porosity. It is below the effects of evaporation or transpiration. No capillary water is lost through gravity. It may be lost, in part, by upward capillary movement into the root-zone. However, this is commonly offset by new supplies from rainfall. When infiltration penetrates down from the surface to this substrata and when a sufficient time-interval exists, then all of the capillary porosity, from the surface to the aforesaid substrata, will be filled. Infiltration will continue without any abstraction by capillary action. The rate of infiltration will be constant. The condition of f_c exists.

All of the foregoing hypothesis is supported by the studies herein presented.

Derivations from the data--As an example, the writer has taken Site 142 at Dayton, Washington: Aphena silt-loam, noncapillary porosity = 26.7 per cent, capillary porosity = 26.7 per cent (see Figs. 1 and 5 and Table 1). The other four sites presented herein were analyzed in a similar manner as 142.

Penetration--The data of Table 1 (Site 142) gives the cumulative amounts of infiltration for five time-periods during the three hours of the initial run. During any hour or time-interval the volume of infiltration, applied at capacity-rate, must equal the volume of the available capillary porosity plus noncapillary porosity. At this moment the exact proportionate division is unknown. If we assume that 100 per cent of the available porosity is filled as infiltration penetrates, then the resulting depth of penetration will be the volume of infiltration divided by the total available porosity per cubic inch of soil. In the top layer (0 to 7 inches) the available capillary porosity is the difference between the soil-moistures preceding and following the initial run. This difference is (27.3 - 12.0) = 15.3 per cent or 0.153 cubic inch per cubic inch of soil (see data, Table 1, Site 142). The non-capillary porosity remains at 26.7 per cent or 0.267 cubic inch per cubic inch of soil. The sum (0.153 + 0.267) = 0.420 inch. The penetration, therefore, during the first 15 minutes of infiltration is (1.71/0.420) = 4.06 inches (see top line in Table 2). This procedure is continued in Table 2 for the entire three-hour period. At three hours the total penetration, under the assumption of 100 per cent, is 16.01 inches [Table 2, Col. (6)]. Note change in available capillary moisture as penetration passes the depths of 7 and 15 inches.

In Table 2 there is also shown (by unbracketed figures) the penetration premised on the estimated actual mean volumes of capillary water absorbed during each of the three initial-run hours. These estimated figures are respectively 80, 60, and 25 per cent of the figures in Table 1, Column (3). The total estimated actual penetration is 18.25 inches in Table 2, Column (6).

The true actual depth of penetration, we later find, is 17 inches at hour three (see paragraph on adjustment).

Volumes of soil-moisture: Initial condition--The volume, 2.14 cubic inches (point A, Fig. 2) is the observed initial moisture-percentages 12.0, 12.8, and 12.8 per cent, multiplied by the respective thickness of the layers penetrated at hour three, namely, 7, 8, and 15 to 17 inches or two inches.

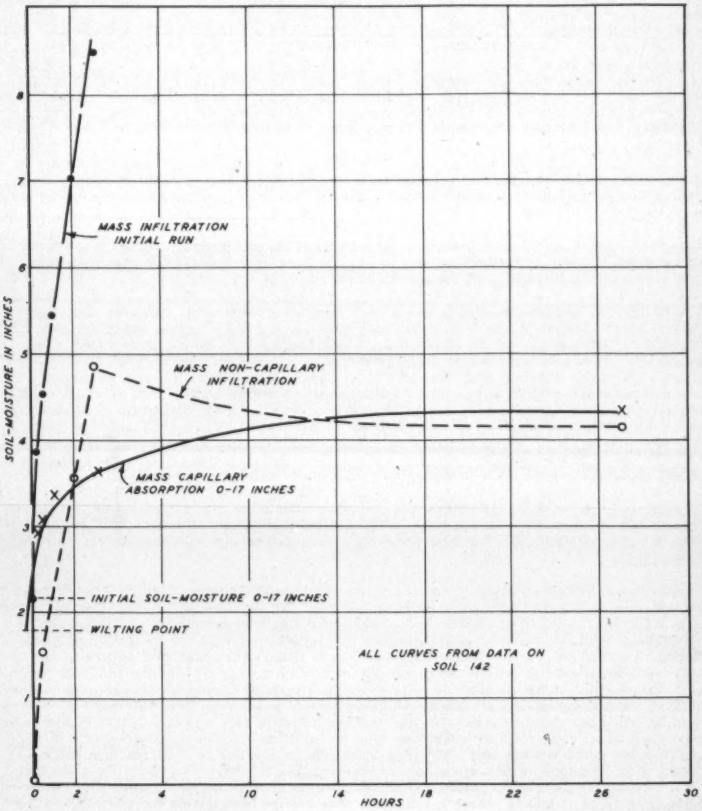

Fig. 2--Example, Site 142, Dayton, Ohio

Table 2--Depth of penetration, initial run, Site 142 (for Fig. 2b)

Time	Vol. of infiltration	Capillary	Non-capillary	Rate =	Penetration (2)/(5)	Penetration Mass
(1)	(2)	(3)	(4)	(5)	. . .	(6)
min or hr	in				in	
0-15	1.71	0.153	0.267	0.420	(4.06)	(4.06)
15-30	0.62	0.153	0.267	0.420	(1.48)	(5.54)
30-60	0.95	0.153	0.267	0.420	(2.26)	(7.80)
or						or
0-60	3.28 at 80%	0.122	0.267	0.389	. . . .	8.45
2d hr	1.60	0.117	0.267	0.384	(4.17)	(11.97)
or	1.60 at 60%	0.070	0.267	0.337	4.78	or 13.23
3d hr	1.46	0.094	0.267	0.361	(4.04)	(16.01)
or	1.46 at 25%	0.024	0.267	0.291	5.02	or 18.25

References for columns: (1) and (2) see p. 45, Bull. 729 (also Table 1); (3) p. 45, Bull. 729; differences in soil-moisture; "Initial" vs. "Wet"; (4) see p. 16, Bull. 729; (5) available space per inch depth of soil-column to receive infiltration; [(2)/(5)] depth in soil-column required to hold the volume of water specified in Col. (2); (6) summation of previous column; total depths of penetration at the given time (Col. 1); figures in parentheses are based on the assumption that 100 per cent of the available capillary porosity is filled during the times of penetration; other figures in Col. (6) are based on the assumption that 80 per cent of the capillary porosity in the upper zone is filled in the first hour and that 60 per cent and 25 per cent of the capillary space in the lower zones are filled during the second and third hours.

Table 3 derives the increasing volumes of capillary soil-moisture during the initial three-hour period. When these points in columns (5) and (6) are platted on top of the initial soil-moisture of 2.14 they are a guide for the points A to B and of the mass-curve of capillary soil-moisture. Note that 2.14 plus 2.06 = 4.20 for point D in Figure 2 (b), also that 2.14 plus 1.49 = 3.63 for point B, Figure 2 (b).

Volume of soil-moisture: Condition at 24 hours after the initial run--This is the volume 4.32 cubic inches at point C (Fig. 2). At hour 27 the volume of capillary water in the 17-inch soil-column has increased 0.70 cubic inch (3.62 at B to 4.32 at C) despite the fact that there has been no infiltration during the 24-hour interval. This increase in capillary moisture occurs at all the other sites. Where did the capillary moisture come from? Obviously it was absorbed from water in the noncapillary channels. There was no other available source.

The phenomena of increased capillary soil-moisture during short intervals between rainfalls--The mass-curve infiltration for the wet run, platted from the data of Table 1, is shown in Figure 3 (b). The f-curve, derived in the usual manner from the mass-curve, is shown in Figure 3 (c). Note the abrupt change in the rate of infiltration during the first hour. Normally, under fairly continuous rainfall, this f-curve would follow the dotted line G-H. The excess volume of infiltration over the normal f-curve is measured by the area FGH. This volume is 0.70 cubic inch. This volume, in the writer's opinion, represents the sinkage of water in the noncapillary channels due to the lateral capillary absorption through some 17 inches of soil. This 0.70 cubic inch, independently computed, from approximate values of (C - B) [Fig. 2 (b)] or (4.32 - 3.63) = 0.69. The same analysis and findings apply to the other sites except possibly Site 24. Further research with special data is needed for definite proof of this hypothesis.

The volumes of capillary absorption or sinkage during the 24-hour interval between runs (rains) is given in Figure 4 for the several sites. Naturally, the site with the driest initial soil-moisture (142) shows the largest volume of capillary absorption. The volume of soil-moisture, at hour 27, to the same depth as at hour three and zero, is at or near 100 per cent of capillary capacity.

Adjustment for actual depth--The trial or approximate depths of penetration for Site 142 were given in Table 2 as 16.01 and 18.25 inches. The true or most exact depth for hour three was found to be 17.0 inches by a "cut-and-try" process. Referring to Figure 2 (b), the soil-moisture volumes at points A and C are derived from different soil-moisture data. The figure used for depth of penetration must be the same in both cases. The true depth will have the same figures for D as for C and there will be close agreement between the figures for B and the figure for C minus the value of

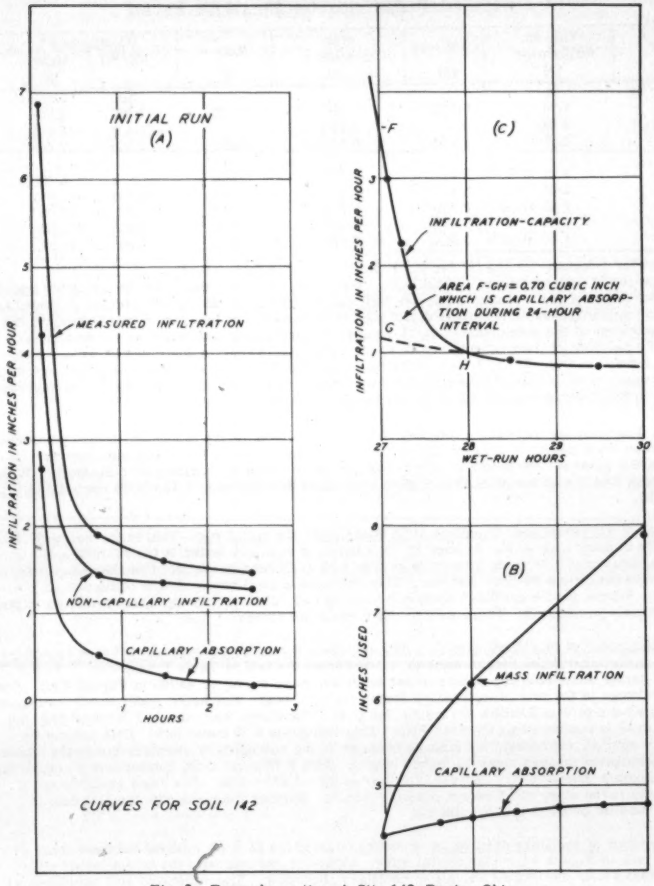

Fig. 3--Example continued, Site 142, Dayton Ohio

sinkage. Trials based on depths 18.0, 17.5, and 17.0 inches were made. The closest agreement occurred when 17.0 inches was used. The resulting figures as used for A, B, D, and C are noted on Figure 2 (b).

This fussy process can be improved, perhaps by the application of the capillary potential equation [Rep. Comm. Soil-Moisture, Trans. Amer. Geophys. Union, p. 303, 1937] in deriving the capillary-intake curve.

Table 3--Volume of "initial" soil-moisture, Site 142 (for Fig. 2b)

Time	Depth	Cap.-vol.	(2)×(3)=Vol.	Mass-volume at	
				100 %	80 - 25 %
(1)	(2)	(3)	(4)	(5)	(6)
min or hr	in		cu in	cu in	cu in
0-15	(4.06)	0.153	(0.621)	0.621	
15-30	(1.48)	0.153	(0.226)	0.847	
30-60	(2.26)	0.153	(0.346)	1.193	
1st hr	8.45	0.122		or	1.040
2d hr	4.17	0.117	(0.489)	1.682	
	4.78	0.070	0.334	or	1.374
3d hr	(4.04)	0.090	(0.380)	2.062	
	5.02	0.024	0.120	or	1.494

References for columns: (2) see Table 2, Col. [(2)/(5)]; (3) see Table 2, Col. (3); (5) and (6) these figures are plotted as dots in Fig. 2 (b); they serve as guide lines for the mass-curve of capillary moisture.

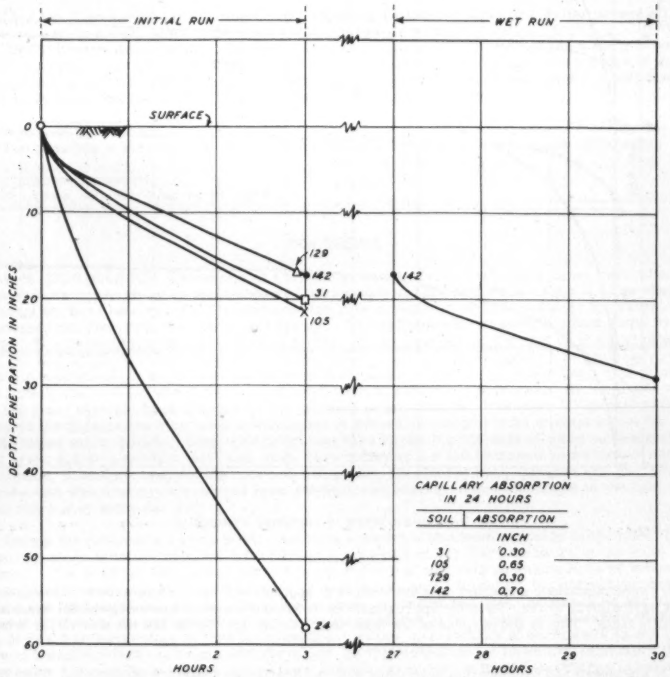

Fig. 4--Rate of penetration of infiltration into the soil

Mass-curve of noncapillary infiltration--The curve shown in Figure 2 (c) was found by subtracting the values of points on capillary curve (b) from the mass-infiltration plus i.s.m. curve (a).

f-curves of infiltration-capacity and rates--These curves are shown in Figure 3. They were derived from the mass-curves. Each designated point on the f-curve is at the middle of a time-interval. The value during the time-interval, as taken from the mass-curve, divided by the time in hours, gives the capacity or rate, f, in inches per hour at the designated midpoint.

Figure 5 shows the curves of capillary absorption for all five sites.

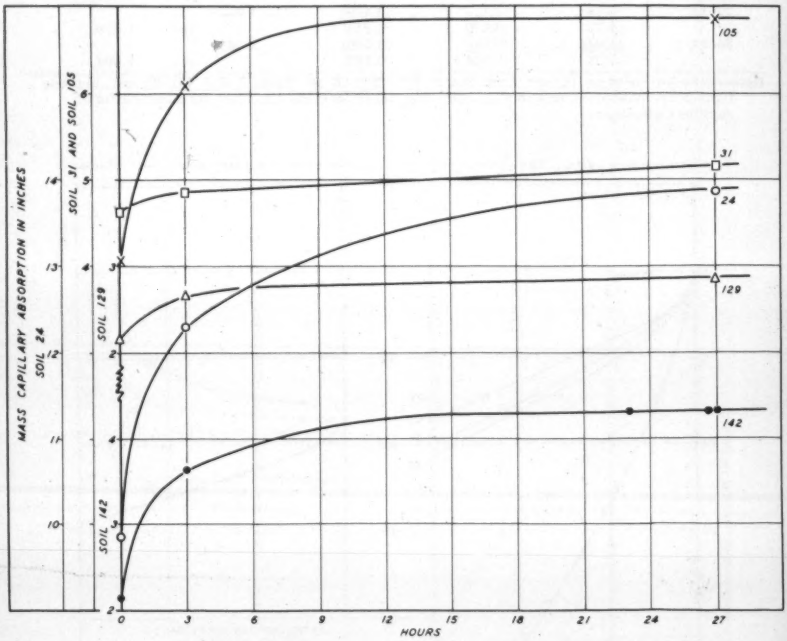

Fig. 5--Mass-curves of capillary absorption

Comments

(1) Approximations and short cuts are needed in applying the infiltration-principle to engineering or agricultural works. Reliable approximations require a thorough knowledge of all basic and scientific facts. That is the purpose of the American Geophysical Union and the motive for this paper.

(2) Engineers and hydrologists have dealt with infiltration as a surface phenomena. They have generally overlooked the pertinent relations developed by agronomists in soil-science and the physics of soil-moisture. The writer in studying these works of the agronomists has experienced some confusion. The agronomist deals mainly with the withdrawal of capillary water by plants, etc. Infiltration is the reverse. It deals with the phenomena of supply. The capillary potential curves are not the same for the two cases.

Rainfall, rain-intensity, infiltration, and infiltration-capacity are all expressed in inches of depth and inches per hour. Why do the agronomists persist in using a cumbersome translation into the metric system?

(3) The data in United States Department of Agriculture Bulletin were almost ideal for this study. It would have been better if the soil-moisture surveys had gone to a depth of at least 36 inches instead of only 25 inches. In a number of sites the increment of soil-moisture between initial and wet runs materially exceeded the volume of applied infiltration. These data were not studied, on the theory that such excess soil-moisture was due to rainfall or other unknown quantities.

Some excellent soil-moisture records are furnished by BOUYOUCOS and MACK at East Lansing, Michigan [Michigan State Coll., Tech. Bull. 172, April, 1940]. The writer, however, could get no data upon which to determine infiltration. There are probably some pertinent lysimeter-data available. At any rate, further research in this line is warranted. It should be undertaken by the State Agricultural Experiment Stations.

(4) The writer, through this study, has made the important finding that the capacity-rates of infiltration are a function of the volume of capillary moisture in the soil-column.

(5) In the Transactions of the American Geophysical Union for 1941, the writer presented an empirical soil-moisture index to be used with the mass-curve of infiltration. CARL F. GIFFY, Assistant Engineer, United States Engineers Office at Rock Island, Illinois, made a study of the change in initial infiltration-capacity during the interval between two or more downpours of rain. He found the apparent anomaly of an increase, instead of a decrease, in the volume of soil-moisture for 15 to 24 hours during a lull. This accords with the writer's finding herein.

By means of the mass-curve of capillary infiltration and the relation stated in paragraph (4), it will be possible to develop a better and more rational scale for use with mass-infiltration.

53 W. Jackson Boulevard,
Chicago 4, Illinois, January 20, 1944

DISCUSSION

A. H. HENDRICKSON (University of California, Davis, California)--This paper calls attention to the need for more study on the problem of infiltration and the factors affecting it. The charge is made that we have been more concerned with the rate of removal of soil-moisture by transpiration and evaporation than with the rate of infiltration. We agriculturists cheerfully plead guilty to the charge. The reasons for this are not hard to find. In the first place, the rate of removal of water from the soil by plants determines the interval between successive irrigations to replenish the available supply and, in the second place, irrigation-water is ordinarily applied and held on soils of relatively flat terrain where the rate of infiltration is not overly important. Agricultural workers, however, have not been unaware of the problem of infiltration. Whenever irrigation-water remains on the surface too long, soil-management is generally changed in an attempt to get the soil to take water more quickly. Studies of irrigation have shown the amounts of water necessary to wet a given soil to a certain depth and, thus, have indicated the total amounts of water and depth of penetration, but, of course, not the rates of infiltration. In other words, farmers are interested in the rate with which water is removed from the soil, and engineers are interested in the rate with which water may enter the soil.

Among the conclusions given in Mr. Sherman's paper, a statement is made to the effect that "capacity-rates of infiltration are a function of the volume of capillary moisture in the soil-column." The question then arises as to how the volume of capillary moisture is to be measured. The moisture-equivalent is frequently used as such a measure. However, the correlation between infiltration- and moisture-equivalents of the 68 soils is exceedingly low. Inasmuch as our experiments indicate that the permanent wilting-percentage seems to be related to the texture of the soil, it would be interesting to have the permanent wilting-percentages of these soils to see if there is a relation between them and infiltration. In this connection it is well to remember that the relation between the moisture-equivalents and the permanent wilting-percentages is not a constant but that, on the contrary, this relationship varies widely.

It is unfortunate that the analysis was made on the basis of only five soils of the original 68 given in Technical Bulletin 729. Of the five soils chosen, two were low both in rate of infiltration

and in organic matter as well as capillary porosity, while the other three were high in infiltration, high in organic matter, and average in capillary porosity. One of these was taken from soil covered with a dense mat of bluegrass-sod, representing a condition of high organic matter content, while two of the others, which fell at the other end of the curve, were apparently chosen from rundown farms. The question then might well be raised as to whether the rate of infiltration was influenced more by the organic-matter residues than by the capillary porosity. At any rate, if one attributes infiltration to capillary porosity, it would be desirable to compare soils of essentially equal organic-matter contents.

In Figure 5 the three soils with the highest infiltration-rates have the highest organic-matter contents and also the highest percentages of capillary porosity. Which one of these factors is responsible for the rate of infiltration is unknown. Plotting the rates of infiltration of all 68 soils against percentage of capillary porosity does not indicate the same relationship as that obtained from the five soils used in the paper. There seems to be some doubt as to whether the five random samples chosen are truly representative of the entire population of soils included in the original publication.

BERTRAM S. BARNES (United States Weather Bureau, Los Angeles, California)--The movements of moisture in the soil are difficult to visualize. In a deep excavation we find that a condition equivalent to submergence exists in a soil-layer extending a few inches above the actual level of standing water in the excavation itself. This layer is the zone of complete capillary saturation, and above it is another zone, or capillary fringe, in which the degree of saturation varies from that of submergence to that of the subsoil zone described by Mr. Sherman as having 100 per cent of its capillary capacity. When the ground-water level recedes, the zone of capillary saturation and the capillary fringe will descend with it, because the fringe will drain by gravity unless there is a submerged layer beneath it.

The capillary fringe and the zone of complete capillary saturation may also be observed when post-holes or other shallow pits are dug soon after heavy rain has fallen, even though the actual ground-water level is many feet below the excavation. In this case, the two zones are slowly moving downward. However, if any moisture is removed from the capillary fringe by evaporation or transpiration, some of the descending moisture in the lower zone will rise again to replace at least a part of it. This fact seems to have been generally overlooked. The process is quite similar to that of the absorption of moisture by the soil within the root-zone, as described by Mr. Sherman.

The writer has found that in Eel River Basin evaporation and transpiration during the first two days following saturation appear to have no effect upon the ultimate soil-moisture deficiency. It is probable that during this period when the rate of evaporation loss is greatest, practically all of the moisture lost is replaced by capillary action from the saturated soil below, at the expense of the ultimate ground-water supply.

Mr. Sherman's theory of absorption is incompatible with the idea of a uniformly thick band of saturation slowly descending through the soil. It suggests, rather, a large number of slender columns of saturation, each surrounded by a cylindrical capillary fringe in which moisture is moving outward from the center. After the soil has absorbed moisture to its field-capacity the fringes may become more heavily charged with water, increasing the size of the columns until they merge and form a layer of saturation.

A few months ago the writer was given some curves prepared by Mr. Sherman, showing the mass-infiltration by hours in six adjoining test plots, during heavy natural rainfall. The plots had different types of vegetal cover, but the soil-structure was believed to be the same in all plots. The f_c-rates varied from 0.10 inch per hour to 0.62. Assuming that f_c represented the constant rate of deep percolation in each case, the writer subtracted the mass-percolation values from the mass-infiltration and constructed mass-curves of absorption. The ordinates represented the momentary soil-moisture deficiency and the abscissas, hours previous to saturation. It was found that a single curve could be applied to all of the plots.

The results of the above study suggest that deep percolation proceeds at a uniform rate during runoff-producing rains, whether the soil is dry or saturated, and that the rate of absorption of soil-moisture is a function of the momentary deficiency alone. The infiltration-rate is the sum of the two and is therefore regulated by the momentary soil-moisture deficiency. It is interesting to note that the different types of vegetation appear to cause great differences in the rate of deep percolation and none at all in the rate of absorption.

RAY K. LINSLEY (United States Weather Bureau, Sacramento, California)--As the author indicates, his hypothesis must be verified by further study of additional data. In the case discussed in his paper, the author finds that capillary water penetrated only 17 inches, yet the net increase in soil-moisture in the upper 25 inches of soil was only 2.96 inches--less than one-half the applied infiltration. Either lateral movement away from the area beneath the test-plot or gravity penetration beyond the 25-inch depth must have occurred. If lateral movement is the cause of the difference, then the entire computation becomes void since the soil-volume is an unknown quantity greater than the unit-column assumed by the author. If gravity flow extended to depths beyond 25 inches, we must conclude that capillary absorption occurred below the 17-inch depth. Since the soil-moisture determinations show less than capillary capacity throughout except for the upper few inches, we might even assume that all the infiltration had been taken up as capillary water. The necessary data for determining the actual behavior would seem to be soil-moisture determinations during, and immediately after, the dry run. This would give a picture of the actual moisture-distribution and would then permit computation of the actual changes during the rainless period.

The rate of change of infiltration in Figure 3(c) is less than during the first hour of the dry run. It is reasonable to assume that drainage of gravity water, drying of the surface soil, shrinkage of soil-colloids, interception on foliage, and other factors might explain all or a part of the high rate during the first hour. The assumption that the area FGH of Figure 3(c) measures the amount of water which changed from noncapillary pore-space to capillary pore-space during the 24-hour dry period, implies that the rate of infiltration is governed in some way by the volume of available noncapillary pore-space, yet from the data it is evident that such space amounted to much more than 0.70 inch at the start of the wet run. It is, therefore, difficult to comprehend the significance of the "sinkage" as determined by the author.

It is interesting to compare the soil-moisture distribution in the test-plots as given in the table of data. Note that for the measurement at hour 27, runs 142, 105, and 24 show the presence of noncapillary water in the upper seven inches, yet are below capillary capacity at the lower depths. Run 31 is just reversed while only run 129 shows the establishment of approximately capillary capacity throughout the full 25 inches. It appears that the initial moisture-distribution in the soil-profile influences the distribution at hour 27. This influence probably is a result of non-uniform characteristics of the various soil-layers.

C. N. JOHNSTON (University of California, Davis, California)--As a reader of the paper submitted by Mr. Sherman, it was found desirable by the writer to make a rather thorough study of that paper together with the data in the foundation paper [see 1 of "References" at end of discussion] from which Mr. Sherman selected his material.

While checking over the computations made by Mr. Sherman, there were several points which seem to be questionable either in the procedure of calculation, the conclusions drawn therefrom, or both. The following presents the writer's analysis of the data used by Mr. Sherman in detailing the behavior of soil 142, Athena silt-loam from near Dayton, Washington.

In the paragraph headed "Penetration", Mr. Sherman presents the procedure used in ascertaining the available capillary pore-space for storage in the first seven inches of soil as 27.3 per cent, the moisture-content at hour 27 less 12.0 per cent, the moisture-content at hour zero. This is acceptable, but if it is presumed the gross pore-space is constant at all depths, the noncapillary pore-space in the first seven inches and that in the lower zones cannot be equal. There seems to be evidence [2] indicating that for any given soil, the gross pore-space is constant and the writer would calculate Mr. Sherman's Table 2 as shown in Table 2 herewith, Columns (1) through (7).

Following the premise of constant total pore-space, Table 2 carries the input-water by time-intervals, but a second change in Sherman's procedure appears in that the depth of penetration for minutes 30 to 60 to consume 0.95 cubic inch [Col. (2)] carries the water from the upper seven-inch zone into the next eight-inch belt where the initial moisture-content was 12.8 per cent and the field-

Table 1--Basic data for soil at Site 142

Porosity		Moisture equivalent	Capillary porosity	Soil-moisture			
Total	Non-capillary			Before run	At depths in inches 0-7	7-15	15-25
....	....	....	....	Initial	12.0	12.8	12.8
53.4	26.7	23.3	26.7	Wet	27.3	24.5	22.2

Table 2--Comparison of Sherman's Tables 2 and 3

L. K. S. Table 2						L. K. S. Table 3				
Time	Volume of infiltration	Gross pore-space	Initial capillary moisture	Volume for storage	Depth penetration	Accumulative depth	Unfilled capillary volume	Capillary absorption	Accum. capillary absorp.	Total available cap. storage to 25 in
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
min	cu in			cu in/in	in	in	cu in/in	cu in	cu in	
0-15	1.71	53.4	12.0	0.414	4.13	4.13	0.153	0.632	0.632	
15-30	0.62	53.4	12.0	0.414	1.497	5.627	0.153	0.229	0.861	
30-60	0.95 = 0.5684 + 0.3816	53.4	12.0	0.414	1.373	7.000	0.153	0.210	1.071	
		53.4	12.8	0.406	0.940	7.940	0.117	0.110	1.181	
60-120	1.60	53.4	12.8	0.406	3.941	11.881	0.117	0.461	1.642	
120-180	1.46 = 1.265 + 0.195	53.4	12.8	0.406	3.119	15.000	0.117	0.365	2.007	
		53.4	12.8	0.406	0.4805	15.480	0.094	0.0452	2.0522	
Next 24 hours					9.5195	25.000	0.094	0.8942	.....	2.9464

Note: Figures carried beyond second decimal for accuracy in arithmetic only.

capacity was 24.5 per cent as noted in the table of basic data. The amount of water necessary to bring the water at saturation 100 per cent to a depth of seven inches in time 30 to 60 minutes is calculated as 0.5684 inch by multiplying depth 1.373 [Col. (6)] by 0.414 cubic inch [Col. (5)], the unfilled volume per inch. At this point, the top seven inches is full of water but in time, 30 to 60 minutes, 0.95 in.h is supplied, so (0.95 - 0.5684) = 0.3816 inch of water will pass on to the next zone (7 inches to 15 inches) [see Col. (2) of Table 2]. The net unfilled pore-space in this next zone is 0.406 [Col. (5)] and, at that storage-capacity, the remaining 0.3816 inch will move downward 0.940 inch. This procedure is continued to the bottom of the Table where it is found that the total penetration by minute 180 is 15.480 inches [Col. (7)] and that by the time depth 25 inches is reached [Col. (7)] 2.946 cubic inches of water could have been absorbed in the available capillary pore-space. Mr. Sherman broke his table up into time-lines that disregarded the changing soil-characteristics so the figures in the writer's Table 2 do not agree with his. Columns (8) through (10) supply the results of calculations for the amount of capillary water stored using the depth [Col. (6)] and the net unfilled capillary pore-space [Col. (8)]. Their product gives the capillary storage accomplished [Col. (9)]. These data correspond to Mr. Sherman's Table 3.

Table 3, herewith, is supplied by the writer to give a better picture of the soil under study before turning to Mr. Sherman's graphs (Figs. 2 to 5 of his paper).

Some of these data are pertinent to the paper under discussion and some offer a check upon previous calculations in Table 2. For example, Columns (4) and (5) show the net filled capillary pore-space previous to making any test to the depths 15.48 inches and 25 inches as 1.9254 inches and 3.144 inches, respectively. Column (9) derives the gross capillary volume to depth 15.48 inches [add 1.9254 inches, Col. (4), to 2.0522 inches, Col. (10), Table 3] as 3.9776. Column (9) gives the figure 3.394 inches as the volume of water that would pass beyond the 25-inch depth when the available capillary pore-space was filled to that depth by the water supplied. The computation just below the Table shows how much further the 3.394 inches that passed beyond the 25-inch depth might go if the soil-conditions stay the same as in the 15- to 25-inch zone. These are pertinent to the general discussion. Columns (6) and (7) give the net and accumulating pore-space with depth to the calculated depth 15.48 inches and to the gross depth, 25 inches, for which information is available. This supplies a check on the amount of water that will just fill the soil to a depth of 15.48 inches or 6.34 cubic inches, the volume put on by the end of hour three.

A graph may now be shown (Fig. 1) which reproduces the writer's data plotting inches of water infiltrated against time as in Mr. Sherman's Figure 2. Curve a and Mr. Sherman's curve a are quite alike, but the writer's curve b starts from the volume 1.9254 inches [Table 3, Col. (4)], which is the initial capillary storage to depth 15.48 inches, not from a volume corresponding to

depth 17 inches as used by Mr. Sherman. Curve b rises to D and then strikes horizontally to C on value 3.977 [Col. (9), Table 3]. Because the value for D contemplated the filling of the available capillary pore-space to the depth 15.48 inches, D had to be on the same horizontal line as C, which is the gross capillary pore-space to depth 15.48 inches.

Curve c of Figure 1 is the difference between curves a and b for the first three hours, but the next 24 hours see the drainage of the noncapillary water to a depth as great as 61 inches (Table 2), so curve c will fall off from its peak at hour three to value zero at hour 27 along some line, probably not exactly the one given.

Because the above Tables satisfactorily account for the water applied, the writer sees no need of estimating the fraction of capillary pore-space filled to various depths (if indeed it is

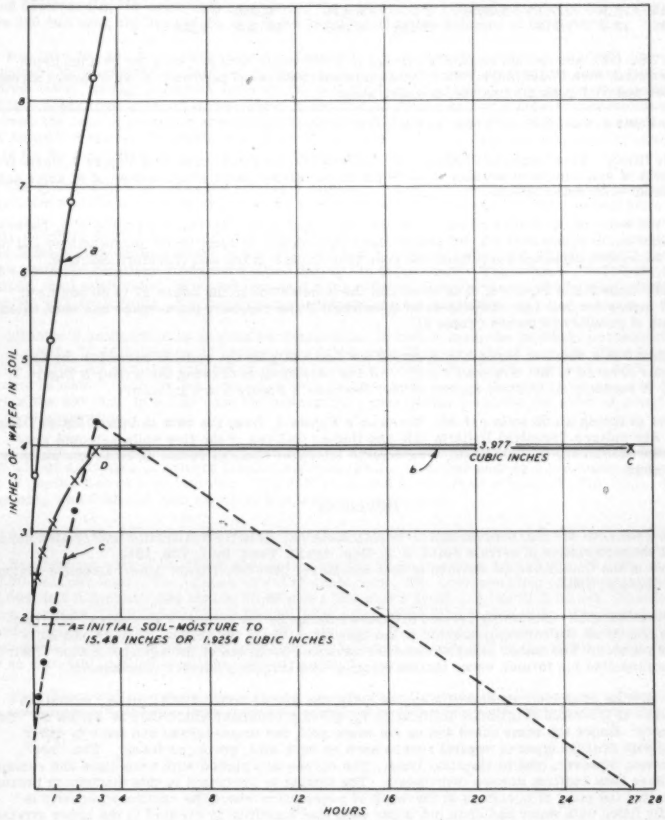

Fig. 1--Graph of inches of water in soil against time

Table 3

Depth	Initial soil-moisture				Available storage		Miscellaneous data		
	Amount	Volume	Total volume to depth	Total volume to depth 25 inches	Net pore-space for given depth	Total net pore-space to depth	Volume put on	Gross capillary volume to 15.48 inches	Volume that passed depth 25 inches
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
in	pct	cu in							
0-7	12.0	0.84	0.84	....	2.898	2.898		1.9254	6.340
7-15	12.8	1.024	1.864	....	3.248	6.146		2.0522 [a]	- 2.946 [b]
								3.9776	3.394
15-15.48	12.8	0.0614	1.9254	....	0.194	6.340			
15.48-25	12.8	1.219		3.144	3.865	10.205	6.34		

From Col. (10), assume net capillary storage at 0.094 cubic inch per inch for 25-inch depth downward; then (3.394/0.094)=36.1 inches possible additional penetration; 25.0 inches already filled and 61.1 possible final depth-penetration.

[a] From Table 2, Col. (10). [b] From Table 2, Col. (11).

partially filled). This seems to eliminate any unknown factors and curve b of Figure 1 starts from the amount of soil-moisture present at the depth of calculated penetration instead of at some point x that needs to be found by trial.

On the basis of the Tables given, the writer feels that in Mr. Sherman's Figure 3(c), the area FGH is the water required to fill the noncapillary pore-space to some depth undetermined and has nothing to do with capillary pore-space because that volume is full and therefore inactive.

In Mr. Sherman's Figure 4, it is noted that the penetration in the hours 27 to 30 begins at depth 17 inches for Soil 142. This is to be questioned if the capillary pore-space has been filled to a depth of possibly 60 inches (Table 2).

Figure 5 is a detail of curve b of Figure 2 for Soil 142 plus the similar curve for the four other soils covered in Mr. Sherman's paper. If the reasoning in drawing the writer's Figure 1, curve b, is correct, all of these curves on Mr. Sherman's Figure 5 are in error.

After graphing all 68 soils per Mr. Sherman's Figure 1, from the data in United States Department of Agriculture Technical Bulletin 729, and finding that two of the five soils selected were hardly representative, it would seem hazardous to interpret findings resulting from any study of the five alone.

References

[1] G. R. FREE, G. M. BROWNING, and G. W. MUSGRAVE, Relative infiltration and related physical characteristics of certain soils, U. S. Dep. Agric. Tech. Bull. 729, 1940.

[2] Report of the Committee on Physics of Soil-Moisture, 1934-35, Trans. Amer. Geophys. Union, pp. 426-432, 1935.

L. K. SHERMAN--Following certain critical remarks by the author of this paper, Mr. Hendrickson points out the accomplishments of the agriculturists in the science of soils and soil-moisture physics. The author acknowledges the advanced progress of the agriculturists. Their work has dispelled his former views that infiltration was largely a surface phenomenon.

Mr. Barnes cites his important finding, namely, the mass-curve of infiltration, minus the mass-curve of the value of ultimate infiltration f_c, gives a resultant which may be called the "net" mass-curve. Under the same rains and on the same soil, the mass-curves and their f_c differ radically with diverse types of vegetal covers such as bare soil, grass, or forest. The "net" mass-curves, however, plat to identical lines. The curves are platted with zero-time and volume at f_c. These data confirm Barnes' hypothesis. The finding is important to this discussion because it proves that the point of f_c occurs at the depth of penetration where the capillary porosity is practically filled with water and does not occur until that condition is created in the upper stratas. When the condition of constant infiltration-rate f_c exists, all of the water entering the soil is

passing through it at a uniform rate toward the ground-water table. There is little or no capillary abstraction. The capillary pores have been filled.

Mr. Johnston has made an independent computation of the author's figures relating to capillary intake and penetration. He adhered to the exact limits at the depth-zones, namely, 7, 15, and 25 inches. The author used the nearest time-period to each zone. In United States Department of Agriculture Bulletin 729 (p. 38), the depth of sampling for Site 142 is given as 0 to 7, 7 to 16 inches. The author assumes that the midzone figures at 0 to 7, 7 to 15, and 15 to 25 inches for all of the 68 sites were interpolated for the three zones as a convenient and uniform means of recording and that the moisture-percentages were fair averages for the arbitrary zones. Mr. Johnston computes the penetration at the end of hour three as 15.48 inches against Sherman's 16.01 inches. The author accepts all of Johnston's figures up to the end of hour three as an estimate based upon the assumption that the volume of capillary water, filling the available capillary porosity, penetrated downward at the same rate as water in the noncapillary channels and filled the available voids 100 per cent, the sum of the two flows being equal to the volumes of infiltration.

Mr. Johnston and Mr. Linsley assume that this is what actually occurred. It could occur but the balance with infiltration does not prove it. Capillary intake and gravity flow follow different physical laws. At high potential, such as dry soil at 12 or 13 per cent, near the wilting-point, the capillary absorption is rapid if free water is available. As the soil-moisture increases toward 26 per cent, the rate of capillary absorption declines until the final absorption-rates are measured in days instead of hours. Probably only 85 or 90 per cent of the capillary porosity was filled at the end of the 30-hour experiment, but that is immaterial, call it 100 per cent.

The question now is: Was the available capillary porosity filled to capacity at the end of hour three? Or was there some material volume of voids left to be filled by capillary absorption of water from the noncapillary storage during the 24-hour lull? In the absence of direct data such as a soil-moisture survey following hour three, or an applicable time-capillary formula, the author made another computation shown in his Tables 2 and 3, assuming that only 80, 50, and 25 per cent of the available capillary voids were filled during the three hours. The volumes, capillary, noncapillary, and infiltration, balanced just as did the original assumption of 100 per cent. Either assumption was reasonable. Neither assumption answered the questions.

Johnston's assumption is as good as Sherman's. In either case, the capillary porosity of the soil at depths 15.48 inches or 17 inches were filled up to 22.2 per cent at hour 27. This leaves (26.7 - 22.2) = 4.5 per cent unfilled capillary porosity at the lower depths and (26.7 - 24.5) = 2.2 per cent in zone 7 to 15 inches unfilled at hour 27 when additional infiltration took place at the start of the wet run. In either case the noncapillary penetration preceded the rates of complete capillary absorption.

Johnston and Linsley further assume that the available soil-moisture value given at depths 15 to 25 inches continues downward indefinitely with (22.2 - 12.8) per cent or 0 094 cubic inch per inch of depth. Let us look into this. The data show that f_c occurred at hour 29 [Fig. 3(c)]. The value of f_c was 0.82 and then capillary absorption became zero.

At hour three, Johnston's figure for the rate of capillary absorption is 0.406 inch per hour.

The average rate of capillary absorption for the 26-hour period 3 to 29 was [(0.406 + 0.0)/2] or 0.20 inch per hour. The volume was 0.52 cubic inch. The corresponding capillary penetration, at 0.094, is 5.5 inches. Add this to 15.48 gives Johnston's depth to f_c as 21.0 inches. Sherman's figure would be [(0.18 + 0.0)/2] = 0.09 and (17.0 + 2.4) gives 19.4 inches to f_c. The soil-moisture at either depth must have been close to 26.7 per cent. The advanced penetration of noncapillary water during hours 27 to 29 could have done it. So could a "sinkage" in the 24-hour lull. There was no material unfilled capillary porosity below 21 inches.

This paper and its valued discussions controvert the "surface-only" theory of infiltration. The investigation with other data should be continued in order to clarify certain points.

SOIL-MOISTURE RECORDS FROM BURNED AND UNBURNED PLOTS IN CERTAIN GRAZING AREAS OF CALIFORNIA

F. J. Veihmeyer and C. N. Johnston

A paper [see 4 of "References" at end of paper] published in the Transactions of the American Geophysical Union, 1938, referred to experiments which showed that plant-transpiration is the chief means by which water is lost from soils, and that the loss of water by evaporation directly from the surface of the soil is almost entirely confined to a shallow surface layer of about four to eight inches It was pointed out that water, when applied to dry soils, is rather quickly distributed until a condition known as the field-capacity is reached. After this, the movement of the water, for practical purposes, may be considered to have ceased. The field-capacity of soils cannot be changed markedly by the addition of organic matter or fertilizers, nor can the amount of water usable by plants be changed materially by the applications of such materials.

The implication these statements have upon the hydrology of grazing areas in California is apparent. Particularly important is the fact that the loss of water from soils is essentially through plant-transpiration and not evaporation from the surface. Denudation of watersheds would then seem to offer a means for increasing water-supplies. While there is insufficient space to permit the presentation of data upon which this statement is based, one example of its application may be cited. The success of the agricultural practice of summer fallow, in so far as soil-moisture is involved, depends upon carrying over the water stored in the soil from one season's rainfall to the next by keeping the land free of vegetation and thus eliminating the draft on the soil-moisture by plant-transpiration.

The ability to store water in soils for use by plants in subsequent seasons is illustrated in Figure 1. This is a view across a ten-acre field at Davis, California, on which barley had been raised continuously for five years. It was used in an experiment in which the area was needed as a unit, but after the plants had become about six inches tall, it was divided up into tenth-acre plots by discing the plants in alleyways 11 feet wide between the plots leaving plots 146 feet long and 30 feet wide. When the picture was taken, the rainfall had been extremely low for this locality, and was sufficient to wet the soil to a depth of only about three feet. The wilted plants (light colored) are clearly evident in the areas that had grown barley the previous seasons while those in the portions of the field where the plants had been destroyed the previous season by cultivating, and thus saving the stored water, show no evidence of shortage of water. The locations of the alleyways between the plots of past seasons are clearly defined. There was enough water in these strips to produce a crop of barley. If there had been much evaporation or if water moved appreciable distances through capillarity, this would not have been the case.

In connection with the work of the Committee of the College of Agriculture of the University of California, which, for the past ten years, has been investigating range-management practices and the effects of denudation by fire on the water-regimen of certain areas, a number of plots and small watersheds have been under observation. Only the records for a few representative plots will be shown.

The test-plots referred to herein are located in Shasta and Tehama counties in the northern part of the State. Instead of designating the plots by number, they were given the name of the soil, or the cover, or the location, or a combination of these. They were selected to represent different conditions of soil and vegetative cover. At each place, adjacent plots were chosen so that they were as near alike as to slope and cover as could be found. In the fall of each year, the vegetation on one of the pairs of plots was cut, piled, and burned. The trash, litter, and small plants which remained were then burned with a blow-torch. This resulted in leaving the soil practically bare. Figure 2 shows the burning of one of the plots near Ono.

In 1940 the plots were burned on September 25. In 1941, however, the burning was not done until December 22. Thus, in this latter year, there was no opportunity for much growth to start on any of the plots until spring, and the plots went through the rainy season bare. The conditions as to clearing, we think, were more severe on all of the plots than would be the case where broadcast burning is practiced. Figure 3 shows one of the plots at Ono in a dense stand of chamise which has been cleared by cutting and burning. The average slope of this plot is about 30 per cent. Incidentally, all but three pairs of plots included in the study in Shasta and Tehama counties are on steep topography.

The denuded areas are large enough so soil-samples taken near the center are far enough away from the adjacent vegetation so that the possibility of extraction of moisture by the encroach-

Fig. 1--Light-colored areas where barley plants wilted and dark-colored areas where they grew vigorously on water stored from previous rains and not drawn upon by plant-transpiration the previous season (illustrates ability to carry over water from one season to next if vegetation is eliminated)

Fig. 2--Burning Ono Plot No. 2, Shasta County

Fig. 3--Ono Plot No. 3 (dense stand of chamise removed by cutting and burning)

Fig. 4--Corning Plot, looking across burned plot toward unburned one, spring of 1943 (gravelly nature of old valley-fill soil indicated by large rocks shown on surface; sampling this soil extremely difficult, but satisfactory records obtained)

Fig. 5--Button Canyon Plot looking toward catchment-tank for measuring runoff and erosion

ment of their roots is avoided. Generally they were from 75 to 100 feet square. For the first year, the plots were only sampled. The next year, areas of 50 by 50 feet on some of the plots were outlined with boards and suitable catchments provided together with measuring devices so that runoff and erosion could be measured. The rainfall at each location was measured by means of standard rain-gages, and in the unburned plots by trough-gages placed under the plants to give some measure of the interception of rain by them.

Samples were taken with a soil-tube [3]. When the work was started, it was thought the difficulties encountered in sampling these gravelly mountain soils would be too great to permit the use of this method. Attempts to use other methods proved unsatisfactory. Sampling by trenching and taking the soil from the face of the trench was ruled out because of the destruction of so much of the area and because of the frequency of the sampling required. Figure 4 is a view of the bare plot on Corning soil. The large rocks encountered in the soil-profile are indicated by those on the

surface. In spite of the great difficulties and the extremely hard labor involved, satisfactory samples were obtained as is evident from the consistent soil-moisture records. In fact, as far as we know, these are the only records taken in sufficient number and frequency to give a satisfactory picture of the moisture-conditions of soils in mountainous grazing-areas.

Figure 5, taken April 24, 1942, is a view looking toward the catchment-tanks for measuring runoff and erosion on the burned Button Canyon Plot. The soil here is yellow or reddish clay grading into bedrock. The parent rock is sandstone and shale occurring in alternating strata. The natural cover of the area is a pure stand of chamise.

Figure 6 gives the soil-moisture record from September 25, 1940, through September, 1941. The soil was sampled in six-inch increments to a depth of 42 inches. Five cores were taken for each depth at each sampling date and composited. Results are the averages for the five samples. The places of sampling were marked by stakes and subsequent samples were taken near these places. The holes were refilled with soil. This procedure was followed on all of the plots.

The Button Canyon Plot was denuded by cutting and burning on September 25, 1940. The rains started during the latter part of October and by the end of December, 13.29 inches had fallen. This was enough to wet the entire soil-profile, which would only have required about 6.4 inches to raise the 42 inches of soil from the permanent wilting-percentage to the moisture-equivalent. It is interesting to note that the moisture-contents were the same in the unburned and burned plots until the rains started; then the moisture-content, as represented by the dotted line, for the burned was higher than on the unburned plot until the entire soil-profile in this plot was raised to its field-capacity. This means either that the infiltration-capacity of the soil on the burned plot was greater than that of the unburned one or that the interception of rain by the vegetative cover reduced the amount of water reaching the soil-surface sufficiently to make the difference. The catch of rain in the trough-gages installed under the brush in the unburned plots was less than in the standard rain-gage on the burned plot, but the variations between the three trough-gages on the unburned plots have been so great we have not attempted to use the data to account for the soil-moisture differences.

With the beginning of the growing season, the moisture-content in the unburned plot decreased at a slightly greater rate than in the burned one, but by the middle of July, all of the readily available water was used in both plots throughout the full depth of soil. The chamise plants sprouted in the spring and by autumn were well grown. The soil-moisture record was duplicated during the next season as shown in Figure 7. In fact, when the tracings, from which the charts for the soil-moisture records were made for each plot in succeeding years, were laid on top of each other, it was found that, with but few exceptions, there was almost perfect agreement. This replication held true for all of the plots for each of the three years they have been sampled.

In the Button Canyon plots, the revegetation due to sprouting of the chamise and the growth of annual grasses and herbs was so rapid that only during the winter months and a short period in early spring was the ground bare. From then on, the ground was partially covered, but the growth was not as dense as that on the unburned plot. The transpiration, however, was sufficient to take all the readily available moisture from the burned plot as is indicated by the flattened portions of the curves from about the middle of July through the remainder of the summer.

Figure 8 gives the record for the Cold Fork plots for the season 1940-41. The slope of these plots is very steep and there was some difficulty in sampling from this cause. The soil is a brownish clay-loam on the surface with chocolate-brown clay-subsoil grading into decomposing shale, and probably should be classed as Hugo. The vegetative cover at this location is chamise with some manzanita. There was rainfall of 13.63 inches up to the end of December which was more than twice as much as the amount, 5.7 inches, required to wet the soil to the full depth of 42 inches. The brush on the burned plot here did not sprout and grow as rapidly as that on the Button Canyon Plot. A number of annual grass species and herbs became established and by the end of the season there was a fine stand. Apparently these grasses and herbs were not deep-rooted enough to take all the readily available water from the full depth of soil, since only in the top six inches of the burned plot was the water-content reduced to that in the unburned plot. The lessened draft on the soil-moisture due to the death early in the season of the annual plants also may account for the difference. There was a difference of 2.06 inches in favor of the burned plot at the end of the growing season.

Figure 9, taken April 21, 1943, is the slope on the burned Holland Plot at which time there was a dense stand of annual grasses. The vegetative cover in this area is principally manzanita with some oak and pine. The soil is typical granitic Holland. The amount of water which can be stored

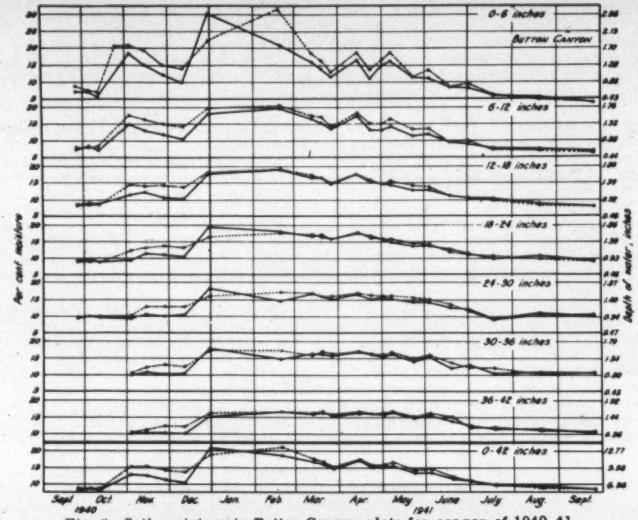

Fig. 6--Soil-moisture in Button Canyon plots for season of 1940-41
(solid line for unburned and dotted line for burned plot)

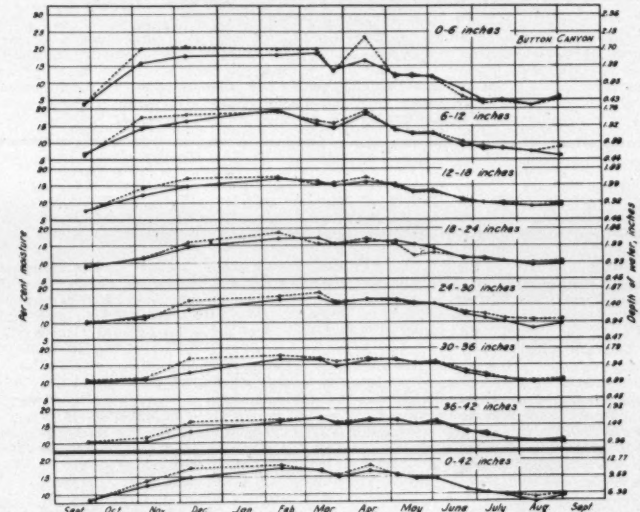

Fig. 7--Soil-moisture in Button Canyon plots for season of 1941-42
(solid line for unburned and dotted line for burned plot)

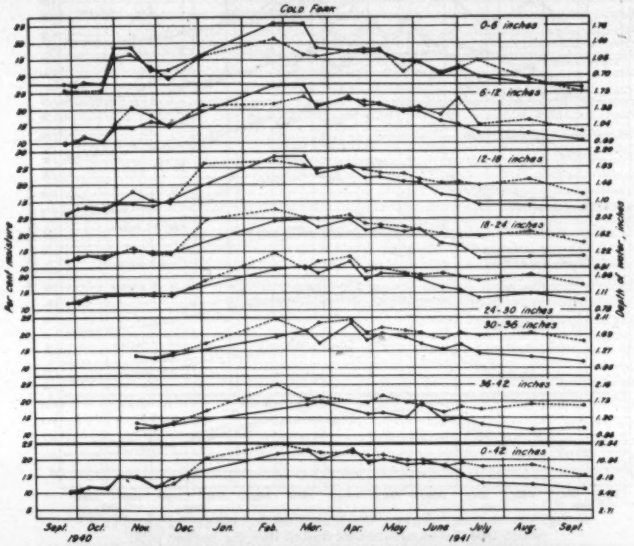

Fig. 8--Soil-moisture in Cold Fork plots for season of 1940-41 (solid line for unburned and dotted line for burned plot)

Fig. 9--The burned Holland Plot, April 21, 1943

in this soil to a depth of 42 inches, as represented by the difference between the field-capacity and the minimum moisture-content in the fall of the year, is 7.6 inches. The brush did not sprout on the burned plot, and the draft on the soil-moisture supply was not as great as in the unburned plot. There was some readily available moisture left in the soil in the burned plot at the end of the season

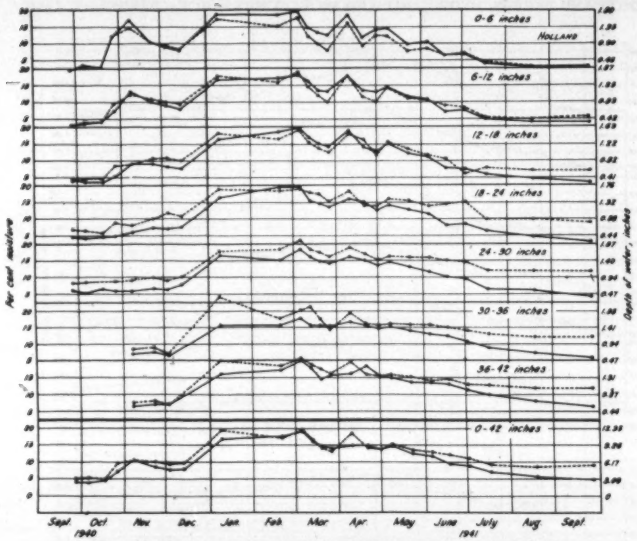

Fig. 10--Soil-moisture in Holland plots for season of 1940-41
(solid line for unburned and dotted line for burned plot)

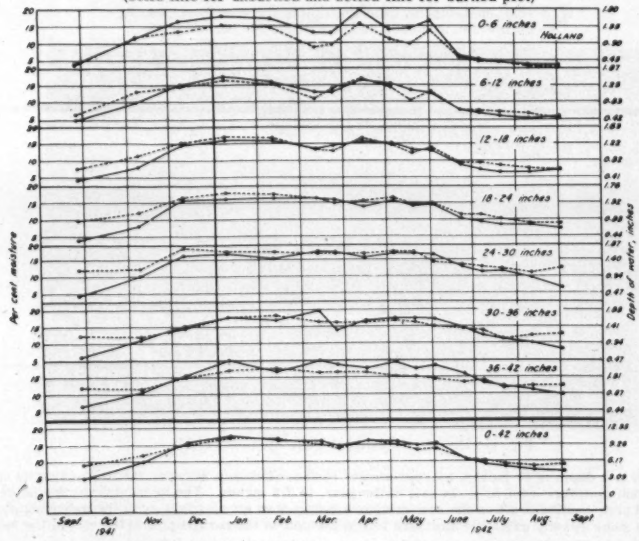

Fig. 11--Soil-moisture in Holland plots for season of 1941-42
(solid line for unburned and dotted line for burned plot)

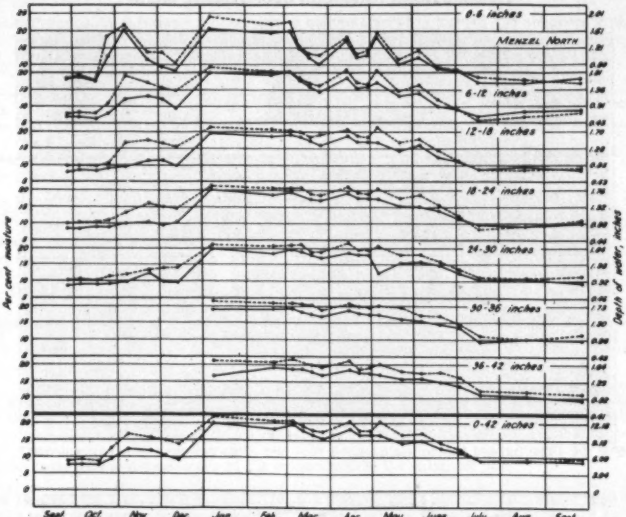

Fig. 12--Soil-moisture in Menzel North plots for season of 1940-41
(solid line for unburned and dotted line for burned plot)

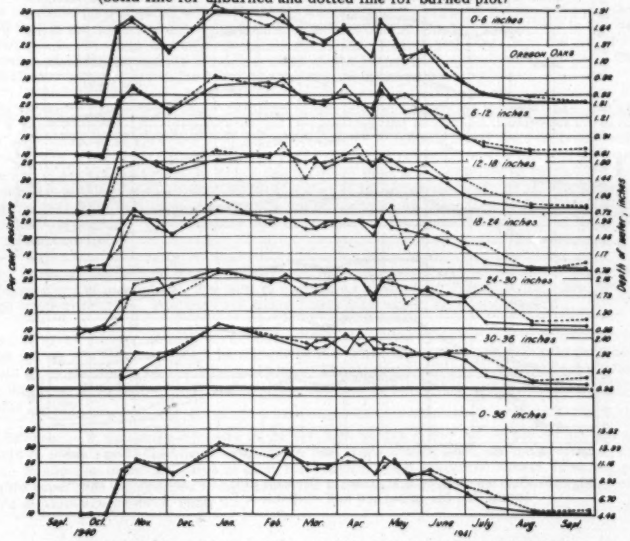

Fig. 13--Soil-moisture in Oregon Oaks plots for season of 1940-41
(solid line for unburned and dotted line for burned plot)

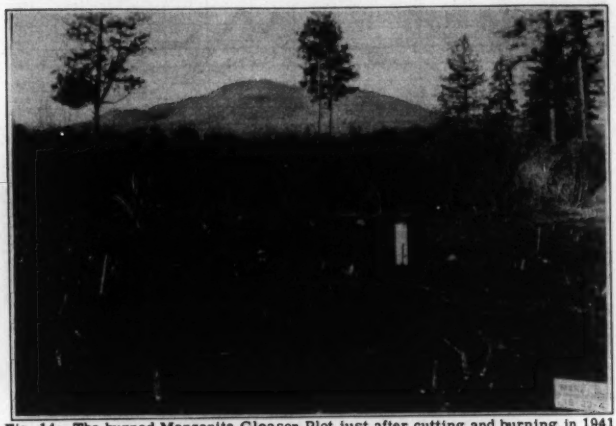

Fig. 14--The burned Manzanita Gleason Plot just after cutting and burning in 1941

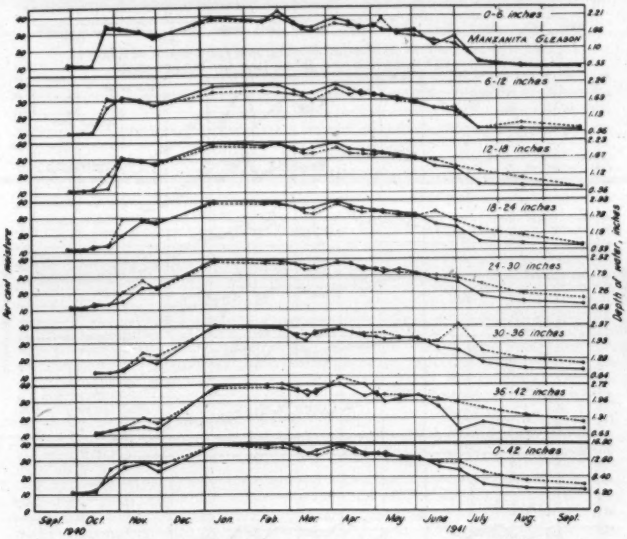

Fig. 15--Soil-moisture in Manzanita Gleason plots for season of 1940-41 (solid line for unburned and dotted line for burned plot)

Table 1--Differences in minimum soil-moisture contents between burned and unburned plots in the fall of 1941

(Minus sign indicates the moisture content of the soil in the unburned was greater than in the burned plot)

Plots	Depth of soil, inches							Full depth of soil
	0-6	6-12	12-18	18-24	24-30	30-36	36-42	
	in	in	in	in	in	in	in	in
Button Canyon	0.03	-0.04	0.01	-0.04	0.07	0.04	0.02	0.08
Cold Fork	-0.09	0.18	0.30	0.32	0.35	0.51	0.58	2.06
Holland	-0.02	0.14	0.28	0.51	0.70	0.59	0.47	2.66
Menzel North	-0.10	-0.07	0.06	0.13	0.18	0.18	0.16	0.55
Manzanita Gleason	0.00	0.10	0.02	0.05	0.23	0.26	0.24	0.90
Oregon Oaks	-0.01	-0.01	0.11	0.03	0.22	0.18	. . .	0.52
Ceanothus Gleason	0.03	0.01	0.33	0.30	0.46	. . .	. . .	1.13
Corning [a]	0.03	0.38	0.35	0.47	0.57	. . .	. . .	1.80
Diamond Range [a]	-0.21	-0.07	0.15	0.14	0.28	0.23	0.16	0.68
Inskip	-0.01	0.15	0.14	0.18	0.15	0.10	. . .	0.71
Menzel South	0.03	0.17	0.22	0.26	0.31	0.32	0.31	1.62
Redding [a]	-0.03	0.02	0.34	0.19	0.12	. . .	. . .	0.64

[a] These soils are old valley-filling materials.

of 1940-41 as shown in Figure 10. This amounted to about 2.66 inches. Figure 11, which gives the record for the Holland plots for the season 1941-42, shows that, due to this carry-over of moisture in the burned plot, the moisture-content in it was above that in the unburned plot until December when the soil throughout its full depth was filled to its field-capacity, but at the end of the summer of 1942, again there was more moisture in the burned than in the unburned plot.

Figure 12 gives the soil-moisture record for the Menzel North plots for the season 1940-41. These plots are located very near the Ono plots. The soil here is typical of the Aiken soil as is that on the Ono experimental area, and it is believed that the soil-moisture in the Menzel North plots may be taken to be similar to that in the Ono plots. The vegetative cover at this site is mostly chamise but includes ceanothus and manzanita. The moisture-content of the burned plot was higher than that in the unburned one until the whole soil-profile in the plot was raised to the field-capacity but, due to the rapid revegetation by the sprouting chamise and annuals at the end of the growing season of 1941, the readily available water in the burned plot was about exhausted. There was only 0.55 inch more water in the burned as compared to the unburned plot.

Figure 13 shows the soil-moisture condition in the Oregon Oaks plots for 1940-41. The cover is largely a stand of scrub oak commonly called Oregon Oak, but dispersed throughout the area are manzanita, ceanothus, and digger pine. The soil is Aiken and 7.4 inches of water are required to refill the full depth of soil at the end of the dry season. There was good recovery of the oaks on the burned plot by the end of the summer, and the transpiration from them was sufficient to reduce the moisture-content in this plot to within 0.52 inch of that in the unburned area. It is interesting to note, however, that there was more moisture in the burned plot as compared to the unburned until about the middle of August. This probably was due to the low transpiration demand by the small plants on the burned plot.

Figure 14 shows the burned Manzanita Gleason Plot. The vegetative cover at the site is an extremely dense stand of manzanita. The soil is classed as a Gleason, is similar to Aiken, and has a very high infiltration-rate. It also has a surprisingly high water-storage capacity.

Figure 15 gives the soil-moisture record for 1940-41. After denudation, the brush started to grow in the spring and was fairly high by the end of the summer, but the transpiration demand was not as much as by the plants on the unburned plots. There was a difference of 0.90 inch of water in the soil in favor of the burned plot at this time. The lag in use in the burned plot is clearly indicated in this Figure.

The differences in moisture-contents in the six-inch depths of the soil in the burned and unburned plots in the fall of 1941, when the moisture was at the lowest level for the season, are given in Table 1. In addition to the six pairs of plots for which the soil-moisture record is shown graphically in this paper, the differences in soil-moisture between the burned and unburned plots of six other pairs of plots are given in Table 1.

In every case, the residual moisture-content of the full depth of soil in the fall and before the beginning of the rainy season was greater in the burned than in the unburned plots. In one case, Button Canyon, there was only 0.08 inch in favor of the burned plot while in others the difference was substantial. In seven cases out of 12, the moisture in the top six inches of soil was greater in the unburned than in the burned plot, and in the six- to 12-inch depth this was true for four out of the 12 cases. In only one case, Button Canyon, in the 18- to 24-inch depth, was the difference in favor of the unburned plots in depths below 12 inches. In general the differences in the surface layers were small whether the plots were burned or not. The differences in soil-moisture are a reflection of the kind of vegetation which grew on the burned plots. In cases where the brush sprouted and grew rapidly, there were slight differences--for example, this was true for the Button Canyon, Menzel North, and Oregon Oaks plots. On the other hand, on those plots where mostly annual grasses grew, the differences were quite large as on the Cold Fork, Holland, Ceanothus Gleason, Corning, and Menzel South plots. The intermediate group, Manzanita Gleason, Diamond Range, Inskip, and Redding, had some revegetation by brush and some grasses.

These results indicate that the losses of moisture were determined by the depth of rooting of the plants and their persistence throughout the growing season. Although some of the annual grasses may have been deep-rooted enough to penetrate the full depth of soil, their early maturity and death would eliminate the draft on the soil-moisture supply during the forepart of the season so that some readily available water was left in the lower depth of soil.

The close agreement between the permanent wilting-percentages determined with sunflowers as a laboratory procedure and the minimum moisture-contents of the lower depths show that all of the readily available water was taken from the soil in the unburned plots. The reduction of the soil-moisture content below the permanent wilting-percentage in the surface six inches, and, in some cases, in the six- to 12-inch depth of soil, indicates that evaporation directly from the surface of the soil was effective in removing some water from the zero- to six-inch depth and, in some of the plots, from part of the six- to 12-inch depth. But it seems clear that transpiration was the principal cause for the loss of moisture below the surface layer.

In taking samples in the plots which were on primary soils, such as those for which the soil-moisture records are given in this report, the soil-tube was driven to the full depth of the soil-mantle at each sampling. Disintegrated bedrock was encountered in each hole and it was not possible to get deeper samples with the method used. Water may have been stored in the crevices of the rocks and in the disintegrated portion between the bedrock and the soil. The fact that the curves showing the extraction of moisture from the unburned plots were almost flat after about the middle of July indicates that the plants were getting very little water from the soil after this date. Since the deep-rooted brush plants did not die, it follows that it is very probable that some additional water was obtained from below the depth of sampling. This amount, doubtless, is very small, and was not sufficient to keep the plants supplied with water since the appearance of the vegetation on the unburned plots at the end of the season indicated signs of a deficient water-supply. The flattened portions of the soil-moisture extraction curves in the burned plots may not always indicate lack of readily available water. For example, the lower depths of soil in the burned Cold Fork plot (Fig. 8) and in the Holland burned plot (Fig. 10) are almost flat due to either the absence of roots or to the death relatively early in the season of the annual grasses on these plots.

The amounts of water which could be stored in the soils each season measured by the difference between the field-capacities and the minimum moisture-contents reached in the unburned plots at the end of the growing season, calculated in inches depth of water from the soil-moisture records for the plots reported herein, together with six additional plots, are given in Table 2.

In some of the charts, moisture-contents higher than the field-capacities were recorded especially in the upper layers of soil. This seeming discrepancy is due to the fact that samples sometimes were taken immediately following rains and the soil was saturated before natural drainage was completed. In general the moisture-equivalents of the soils agreed with the estimated field-capacities.

It is interesting to note that the amounts of water required to refill the soil-reservoir in the unburned plots are in line with the difference between rainfall and runoff for the three principal watersheds in this general area as reported by A. F. MEYER [2]: For the Sacramento at Red Bluff, 11.8 inches; the Pit, 10.9 inches; and the McCloud, 7.9 inches.

Usually, runoff has not been recorded from our plots until there have been rains of about the amounts of water given in Table 1. Of course, the character of the storms will have great influence upon the runoff. For the season 1943-44, there was runoff from only a few of the plots

Table 2--Field-capacities and minimum moisture-contents reached in the unburned plots at the end of the growing season (Difference in inches in these values is the amount of water required to wet the soil)

Plot	Depth of soil	Field-capacity	Minimum soil-moisture-content[a]	Difference between field-capacity and minimum moisture-content	
	in	pct	pct	pct	in
Button Canyon	42	18.2	8.2	10.0	6.4
Cold Fork	42	22.0	11.5	10.5	5.7
Holland	42	17.0	4.8	12.2	7.6
Manzanita Gleason	42	35.0	12.0	23.0	9.7
Menzel North	42	20.0	8.0	12.0	7.3
Oregon Oaks	36	26.0	9.5	16.5	7.4
Ceanothus Gleason	30	29.0	9.5	19.5	6.7
Corning	30	25.0	9.5	15.5	5.5
Diamond Range	42	23.0	11.0	12.0	6.7
Inskip	42	40.0	14.0	26.0	10.0
Menzel South	42	20.0	8.5	11.5	7.1
Redding	30	23.0	6.5	16.5	6.0

[a] These values are somewhat lower than the permanent wilting-percentages because of the reduction of the moisture-content below the permanent wilting-percentages in the surface-layer.

Table 3--Runoff and erosion from the Ono Experimental plots

Plots	1939-40		1940-41		1941-42		1942-43	
	Runoff	Erosion	Runoff	Erosion	Runoff	Erosion	Runoff	Erosion
	cu ft	lb	cu ft	lb	cu ft	lb	cu ft	lb
Ono 2								
Covered	1811	208.3	2492	69.7	312	16.2	107	2.8
Denuded	1228	64.6	1691	20.3	290	9.0	46	1.0
Ono 3								
Covered	3185	63.8	4386	46.5	1793	16.3	303	1.9
Denuded	3451	192.6	4748	85.7	1874	40.0	561	14.8
Ono 4								
Covered	952	36.9	1317	13.7	279	5.5	10	0.7
Denuded	924	1.6	1180	1.4	268	1.2	44	0.2

and this was much less than in previous seasons. If the rains come in small amounts and with intensities less than the infiltration-capacities of the soils, there will be no surface runoff.

These amounts of water given in Table 2 represent the total which can be stored in the soil and subsequently taken from it by evaporation and transpiration [1]. To get the total loss from a watershed-area, there should be added the losses which occur by evaporation and transpiration during the winter months. We have been unable to determine the use of water during the rainy season because of the frequency of the rains. After the soil-mantle became filled to its field-capacity, it remained so until the beginning of the growing season. Samplings immediately after rains sometimes showed moisture-contents higher than the field-capacities, but this condition did not persist for long. Our data indicate that the losses from December through March were slight. It should also be mentioned that usually the rainfall during the growing season is negligible.

Measurements of the amounts of runoff and erosion from the plots have been made, but for most of them, these records have not been obtained for enough years to be conclusive. The Ono plots have been under observation for a longer period than the others. The measurements of runoff and erosion from these plots for the past four years are given in Table 3. The differences between burned and unburned plots have not been marked nor have they been consistently in favor of either one or the other. The shorter records for the other plots give similar results.

Summary

The records of soil-moisture conditions in paired plots, one of which was denuded annually by cutting and burning and the other left undisturbed, are presented. The selection of the location for

the experimental plots was governed by the type of vegetative cover, soil, and topographical conditions. The plots for which records are presented in this paper are believed to be representative of large areas in the northern part of California which have potential value for grazing if cleared by burning.

Denudation by burning did not prevent the soil from becoming wet throughout its full depth as soon as that in the unburned plots. In fact, in most cases, the soil was wet earlier in the season in the burned plots than in the unburned ones. The interception of rain by the vegetation on the unburned plots may have been great enough to account for this difference by preventing the water from reaching the soil-surface. Water, however, did get into the soil of the burned plots as the records show and burning did not delay this process in comparison with the unburned plots. The soil-moisture records indicate that the infiltration-capacity of the soils on the burned plots was not impaired.

Evaporation and transpiration were sufficient to dry out the soil in the top six inches of all of the plots, but below this depth transpiration seemed to determine soil-moisture losses. In seven out of 12 cases, there was greater loss of moisture from this surface layer in the burned than in the unburned plots. In the six- to 12-inch depths of soil, four out of 12 cases showed greater loss from the burned plots and only in one case in the soil below the 12-inch depth was there a six-inch layer with greater loss in the burned plot as compared to the unburned one, and this difference was very small. In every case, the total loss for the full depth of soil was less in the burned than in the unburned plots.

The extraction of moisture from the soil seems to depend upon the ability of the species of plants which grow after burning to extend their roots throughout the full depth of soil and upon the persistency of the plants throughout the growing season. In every case in the unburned plots, the moisture-content of all of the soil was reduced to the permanent wilting-percentage. On the other hand, on those plots where the brush did not sprout and where the grasses grew for a short time early in the season, the soil-moisture, except in the surface layer, was not reduced to the permanent wilting-percentage. Under such conditions burning will result in the saving of water and, at the same time, in the production of forage.

The records indicate that runoff and erosion were not accelerated on the burned plots in the areas where these experiments were conducted.

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DISCUSSION

P. B. ROWE, (United States Forest Service, Berkeley, California)--Soil-moisture relations embrace an important, if somewhat neglected, phase of watershed-hydrology. Consideration of soil-moisture relations, particularly as they affect infiltration, soil and subsurface water-storage, and evaporation-transpiration losses, is essential in any quantitative analysis aimed at evaluating the influences of vegetation or land use on water-yield and stream-flow. In presenting original data on soil-moisture, this paper is an important contribution to this meeting.

The outstanding and perhaps best-substantiated finding of the study is that evaporation-transpiration losses of moisture stored in the soil at the end of the rainy season are not appreciably reduced by annual burning of chaparral or woodland vegetation. This, in general, is in agreement with the results of similar studies carried on during the past ten years by the California Forest and Range Experiment Station in chaparral and woodland areas of central and southern California. In the Station's studies, however, evaporation-losses from the soil, particularly from the soil of the annually burned plots, constituted a somewhat greater proportion of the total evaporation-transpiration losses than those indicated by the data given in this paper.

Moisture-studies in a Holland sandy clay-loam soil in the woodland-chaparral type of the Sierra Nevada foothills at North Fork showed that during the summer dry season the moisture-contents of the zero- to four-inch soil-depth of undisturbed plots and the zero- to eight-inch soil-depth of annually burned plots were reduced to zero to two per cent of oven dryness. The moisture in the soils of both plots was reduced well below the wilting-point to depths averaging more than 30 inches. In the 30- to 48-inch depths, soil-moisture remained near the wilting-point and was usually slightly greater for the annually burned than for the undisturbed vegetation plots.

In a third plot, trenched below the depth of root-penetration and maintained completely free of vegetation to avoid transpiration-losses, the moisture-content of the entire 48-inch soil-profile was far below field-capacity at the end of each summer. An average of less than 30 per cent of the available water stored in the soil at the close of the rainy season remained by the end of the summer dry season. Although evaporation was probably not the sole cause of moisture-loss from this soil, the results indicate that evaporation from bare soils, particularly from shallow soils, may under certain conditions be very high. These findings of the North Fork studies have in general been confirmed by the results of similar more recent studies carried on in chaparral types of the San Dimas Experimental Forest in southern California.

Evaporation from the soil of the undisturbed vegetation plots at North Fork accounted for about 0.4 of the total soil evaporation-transpiration losses during the winter rainy season, when the surface soil-moisture content was high. From the annually burned plots it was about 0.6. The evaporation-transpiration losses of the undisturbed vegetation plots during the winter, however, were slightly greater than those of the annually burned plots. It appears likely that soil-moisture contents shown by the data in the paper under discussion as slightly lower for some of the unburned than for comparable burned plots may have been influenced more by such differences in winter evaporation-transpiration rates than by differences in infiltration.

Interception of precipitation by the vegetation may also greatly influence the soil-moisture relations of undisturbed plots. Measurements of interception in a moderately dense chaparral stand at North Fork showed that about 20 per cent of the annual precipitation was intercepted by the brush-cover. About 75 per cent of the intercepted precipitation, however, was carried to the soil as flow down the stems of the plants, and about 25 per cent was lost by direct evaporation from the vegetation cover. Such effects of interception result in an uneven distribution of the precipitation reaching the soil, which, if not taken into consideration in soil-sampling, can result in considerable error in moisture-measurements.

It is interesting that the results of studies reported in the paper indicate that annual burning of the vegetation had so little effect on surface runoff and erosion. The results of 15 years of rather extensive runoff- and erosion-plot and infiltration studies carried on by the California Station in woodland and chaparral types of the State show that burning of the vegetation has, almost without exception, resulted in decreased infiltration-capacities and increased surface runoff and erosion-rates. Infiltration-surveys made in connection with flood-control surveys by the United States Department of Agriculture in the Pajaro, Santa Maria, and Santa Ynez river drainages, and including more than 600 infiltration-capacity measurements, show that burning of the chaparral and forest cover in these watersheds resulted in reduced infiltration-capacities of all the soils tested. Findings closely parallel to these have also been reported by Dr. A. W. SAMPSON of the University of California as a result of his investigations in the chaparral and woodland types of northern California.

Had only small amounts of surface runoff been shown for the plot-studies reported by Veihmeyer and Johnston, the apparent lack of any appreciable influence of annual burning on runoff might reasonably have been attributed to inherently high infiltration-capacities of the soil. The fact, however, that the amounts of surface runoff and erosion from some of the plots were high suggests the possibility that the areas sampled may in the past have been subjected to repeated burnings and subsequent heavy grazing, and that the resulting reductions in infiltration-capacities have carried over into the period of study. In other words, the period of regrowth of the present vegetation since the last burnings may not have been long enough to restore the natural infiltration-capacities of the soils. This assumption appears particularly plausible for the plots in chamise cover. Chamise is a fire type, often indicative of recurrent burning, overgrazing, and deteriorated soil-conditions.

In working with small runoff-plots, the Experiment Station has found that, owing to the wide variations in infiltration, runoff, and drainage-relations of soils, it is extremely difficult to select paired runoff-erosion plots that will yield comparable results. Even though the greatest care is exercised in the selection of plots it has proved advisable at least to duplicate conditions sampled

and to operate the plots through a long enough period of calibration to discover and evaluate any inherent differences before experimental treatment is started.

The authors have emphasized the fact that the records of runoff and erosion for the plots should be continued for a longer period before the results may be considered conclusive. Additional data will be most helpful in evaluating the results of the studies of runoff and erosion, and it is to be hoped that the authors' time will permit them to continue these observations.

HENRY W. ANDERSON (Department of Forestry, University of California, Berkeley, California, by letter)--The statement made previously by Veihmeyer [see 6 of "References" at end of discussion] is repeated in this paper that the field-capacities of soils cannot be markedly changed by the addition of organic matter, and that the amount of usable water which can be stored in soils is also unaffected by the application of organic matter. His data in that article show an increase in the moisture-equivalent which ranged from 5.3 per cent upon the addition of organic matter to a clay to 86 per cent upon the addition of organic matter to a fine sand. His data show no consistent increase in the available water (moisture-equivalent minus wilting-percentage) with the addition of organic matter to the soils, but the results do not seem conclusive because of an unsatisfactory statistical approach to the problem. Incidentally, he did not determine the moisture-equivalent of the organic matter that he added to the soil. Moreover, several other investigators have found marked increases in the available water associated with increases in the organic-matter content of the soil.

FEUSTAL and BYERS [4] mixed peat moss (1/5 and 1/2 by volume) with soils of three textures, clay-loam, loamy fine sand, and quartz sand. They found that in every case the moisture-equivalent of the mixture was higher than that of the soil alone, the increase ranging from a low of only 6.9 per cent for the clay-loam (with 1/5 organic matter) to a high of 807 per cent for the quartz sand (with 1/2 organic matter). In every case the wilting-percentage also increased with the addition of organic matter. For the clay-loam with 1/5 organic matter, the increase in the wilting-percentage was equal to the increase in the moisture-equivalent, so there was no increase in the indicated available water. In all other cases, there was an increase in the available water, which ranged from 26 per cent for the clay-loam (with 1/2 organic matter) to 840 per cent for the quartz sand (with 1/2 organic matter). The loamy fine-sand values were intermediate between those of the clay-loam and the quartz sand. COILE'S [1] results were in general the same as Feustal and Byer's except that he found that the wilting-percentage of heavy-textured soils appeared to be but little affected by incorporated organic matter. Data of DAUBENMIRE and COLWELL [3], of RENNER [5], and of CROFT, WOODWARD, and ANDERSON [2] indicate an increase in the moisture-equivalent with an increase in organic matter.

It is recognized that the moisture-equivalent undermeasures the field-capacity of sandy soils; also some data indicate that the moisture-equivalent undermeasures the field-capacity of coarse organic matter. So when sandy soils or soils high in organic matter are being studied, extreme care must be exercised in using the moisture-equivalent as a measure of the field-capacity.

The indications are that the amount of organic matter in the soil may have considerable influence on the soil-moisture "constants". In the study of water-soil relations under different treatments, consideration should be given to the magnitude of any accompanying changes in the organic-matter content of the soil and their effect on the soil-moisture "constants"

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F. J VEIHMEYER and C. N. JOHNSTON--Mr. Rowe states that our results show "that evaporation-transpiration losses of moisture stored in the soil at the end of the rainy season are

not appreciably reduced by annual burning." It is true that in some cases there was only slight reduction in losses of moisture. As shown in Table 1 of the paper, the difference in soil-moisture content was in favor of the burned plots in every case but that where the burned plots were re-vegetated by the sprouting brush, the differences were small. On the other hand, where grasses and herbs grew, there was appreciable saving of water. For instance, the burned Holland Plot had 2.66 inches more water at the end of the growing season than the unburned one. This is equal to 35 per cent of the total water, 7.6 inches, required to wet this soil. The savings on the Cold Fork Plot equalled 36.1, on the Corning, 33.7, Menzel South 22.8, and Ceanothus Gleason 17.5 per cent.

The data show that denudation will result in a reduction of soil-moisture losses, but that the amounts of water saved are appreciable only where the burned areas are not revegetated by the sprouting brush. Where grasses and herbs follow burning, there is substantial saving of water and at the same time desirable forage is produced.

Mr. Rowe points out that the use of water by the plants on the unburned plots during the rainy season may be the cause for the difference in soil-moisture contents between these and the burned ones. During the winter months, our soil-moisture curves are substantially the same for both the unburned and burned plots. We had hoped to be able to determine the use of water by the vegetation during this time but the rains were so frequent during the three years the plots were sampled that we were unable to get periods during the winter free of rain long enough to detect with certainty the slope of the moisture-curves. There may have been enough use of water by the plants during the early fall months after the rains started to cause the soil-moisture in the covered to be lower than in the burned plots, but we believe if a reason for the difference other than increased infiltration in the denuded plots is sought for, that interception of rain by the vegetation is the most likely explanation. The fact is, however, denudation did not prevent the wetting of the soil-mantle in the burned plots and in most cases this was accomplished at an earlier date than in the unburned ones.

Mr. Rowe raises the question of flow of the rain down the stem of the plants and suggests that resulting uneven distribution of the precipitation reaching the soil can result in considerable error in moisture-measurements. It would seem that in view of the frequency and number of samples taken that if there were appreciable masses of soil wetted by the stem-flow, they would have been encountered. During the rainy season, all of the soil was filled to its field-capacity and remained so until the beginning of the growing season. We believe, furthermore, that there was no portion of the soil in the unburned plots which was not depleted of its readily available moisture by the end of the growing season.

The results of the studies of LUNT [see 3 of "References" at end of discussion] are germane to this discussion. Lunt concluded from a study of the distribution of soil-moisture during a dry period in summer under individual trees that "in practically all cases the lowest moisture-content was found immediately beneath the crown close to the base of the trees", and that "relative wetness values were lowest in the immediate vicinity of the tree-base and they increased in regular zones with increased distance from the trunk, and with depth."

Mr. Rowe's belief that the infiltration-capacities of the soils included in our experimental plots were impaired by burning and heavy grazing in the past is based on the a priori reasoning that burning deteriorates soil-conditions. That this reasoning is untenable is attested to by the results of the studies of SREENIVASAN and AURANGABADKAR [5], who state that "fire-heating results in a marked improvement in the physical texture and degree of aggregation of the soil-colloids." WAHLENBERG, GREENE, and REED [7] also found that "burning and grazing did not result in serious soil-degradation. Burned-over soils exhibited slightly favorable chemical characteristics and unfavorable physical characteristics in comparison with unburned soils." PECHANEC and STEWART [4] show that "increased usability and greater grazing capacity of the range without damage to adjacent property are dependable results of planned burning", and also found that "soil-losses from planned burning were light, and soil-movement, accelerated to some extent immediately after burning, was arrested almost completely by the end of the first spring season."

It is unlikely that any areas in California could be found for experimental purposes which at some time had not been burned. Certainly, the woodland-chaparral type of the Sierra-Nevada foothills at North Fork and the chaparral types of the San Dimas Experimental Area in southern California must have been burned over many times in the past, and results from studies of runoff and erosion from them would likewise be subject to the same criticism if soil-conditions do change as a result of fires in the past. In any event, we are concerned with the effect of removal of the unwanted brush by burning on the water-regimen of the area under investigation, and, since the results so far obtained from our experimental plots show that runoff and erosion are not accelerated by burning, the practice should not be condemned.

Mr. Anderson's discussion is not relevant to the main thesis of the paper; he has raised, however, some questions which need reply. Of course, the addition to soils of any material with high water-holding capacity such as the manure, used in the experiments referred to, whose moisture-equivalent may be well over 100 per cent, will increase the water-holding capacity of the soil. The increase, however, even with such tremendous quantities as 200 tons per acre was not marked, being only 0.4 inch for sand, 0.2 inch and 0.3 inch for the sandy loam, silt-loam, loam, and clay, although on a percentage-basis, they may seem so. When a comparison is made between the 200-ton per acre application and the amount of litter found on the forest-floor under chaparral for an area in San Gabriel Mountains [1], and an accumulation on an average of about 0.6 metric ton per acre [2], it seems unlikely that the moisture-relations of the soil would markedly be affected by denudation.

The extremely high water-holding capacities of organic materials have led to misunderstanding as to their value in increasing the actual quantity of water which can be held by soil-mixtures. Simple calculations based on the relative volumes and weights of the organic material and that of the mineral soil indicate the futility of attempting to change markedly the water-relations of soils by the addition of organic materials. FEUSTEL and BYERS [Anderson's reference 4] stated that their evidence indicates "little or no economy resulting from the admixture of peat in quantities as large as equal proportions by volume." FEUSTEL [6, p. 330] later says that "the effect of organic-material addition to soils on the resulting moisture-holding capacities has been considerably overestimated. The fact that organic materials generally possess moisture-holding capacities much greater than those of mineral-soil materials has led to erroneous conclusions regarding the actual quantity of water held by mixtures of soil organic matter as compared with soil alone." For further discussion on the effect of organic matter on the water-holding capacities of soils see an additional reference [6].

The reference to COILE'S statement [Anderson's reference 1] does not permit his results to be evaluated since only an abstract is published. He does say, however, that organic matter greatly increases the moisture-equivalent of light-textured soil, but we do not know how much increase there was in actual quantity of water.

DAUBENMIRE and COLWELL'S [Anderson's reference 3] differences in moisture-equivalents may have been due to the difference in clay-content in the soil from the two different sites, as indicated by the textural differences of the soils given in their Table V.

RENNER'S statement [Anderson's reference 5] that the ability of the soil to hold water depends largely on the content of organic matter needs further substantiation. High correlation between clay-content and water-holding capacity might also be found and unless it is certain that the comparison is made between soils of the same mineral composition but vary only in organic-matter content, false conclusions may be reached. A similar criticism may be made to Anderson's reference [2] to the work of CROFT, WOODWARD, and ANDERSON. If, as in their Figure 1, the moisture-equivalent had been plotted against clay-content, the same high correlation might have been obtained.

It seems to us that the best procedure to test the effect on the water-properties of soils by their addition of organic matter is to mix them with the soil on the basis of tons per acre and to record the results as inches of water. When this is done, it is clear that the actual increase in quantity of water held by the soil is very slight even with additions greatly in excess of that possible in practical farming operations, or that likely to be encountered as organic litter on brush-covered areas in California which have potential value for grazing.

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REPORTS AND PAPERS

REGIONAL MEETING, SOUTH PACIFIC AREA

WESTERN SNOW-CONFERENCE

SNOW-SURVEYORS' DINNER, FRIDAY EVENING, FEBRUARY 18, 1944

Minutes

The snow-surveyors' dinner was held Friday evening, February 18, 1944, in the Blue and Gold Room of the Claremont Hotel, Berkeley, California. Forty-two members and guests were present. After dinner had been served the meeting was called to order by L. STANDISH HALL, Hydraulic Engineer of the East Bay Municipal Utility District, who served as toastmaster for the evening.

Mr. Hall first introduced the members of the Western Snow-Conference Executive Committee who were present. These included: HARRY L. POTTS, Denver Water Board, Denver, Colorado; R. A. WORK, Irrigation Engineer, United States Division of Irrigation and Oregon Experiment Station, Medford, Oregon; WM. A. LANG, Chief Hydrographer, Southern California Edison Company, Los Angeles, California; and FRED PAGET, California State Division of Water Resources, Sacramento, California. Two other members of the Executive Committee, DEAN CLYDE and RALPH PARSHALL, were attending an overlapping meeting in Los Angeles and missed the dinner. They arrived in Berkeley during the morning session on February 19, 1944. Professor H. P. BOARDMAN, who had carried the load in arranging the Berkeley program, was unable to attend because of a serious auto accident suffered by Mrs. Boardman. Another Executive Committee member, Professor JOSEPH KITTREDGE, University of California, scheduled to be Chairman of the session on February 19, 1944, was ill in bed with flu.

Guests were then introduced as follows:

ROSCOE BRIGGS, United States Geological Survey, San Francisco Office, introduced as his guest J. C. MARTIN of the University of California Chemistry Department.

PERCY BOSANKO, Nevada Irrigation District, introduced as his guest MALCOLM J. BELL of the Otis Elevator Company, San Francisco.

ARCH WORK introduced as his guest FRANK B. HARPER, Head of Current Information Section, Soil Conservation Service, Portland, Oregon.

Mr. Hall introduced as his guest J. S. LONGWELL, Chief Engineer and General Manager, East Bay Municipal Utility District.

Chairman Hall then called for a round-table introduction and the rest of those present stood up each in turn, announcing his name and business affiliation.

Those members who have the responsibility of issuing forecasts in their respective areas then reported on the success of their prognostications for 1943. Dr. CHURCH reported the success of his own work on the Humboldt and of Professor BOARDMAN'S forecasting on the east side Sierra streams. Dr. Church also summarized Mr. FRAME'S report for British Columbia. ARCH WORK reported for Oregon, and also presented Mr. MARR'S reports of forecast-accuracy for the Columbia Basin during 1942 and 1943, W. A. LANG reported his success on the head-waters of the San Joaquin River, L. STANDISH HALL reported on the Mokelumne River, and FRED PAGET reported for the State of California as a whole. The candid reports of near misses and failures with the causes therefor brought from Mr. Longwell the advertisement of a dairy in California: "Our cows are not contented. They are always trying to do better."

W. A. Lang then read a message from N. B. HINSON, Chairman of the Pacific Southwest Power Interchange Committee, on the importance of forecasts of precipitation and runoff to the operation of the Pacific Southwest Power Interchange Committee, stressing the value of the information gained from the snow-surveys in budgeting the State's resources in a period such as this.

WALTER HERZ of the Sierra Pacific Power Company then showed his colored film "Winter in the high Sierras" and another reel covering mountain winter scenery in Oregon and Washington.

A discussion of the different types of rain- and snow-gages and other apparatus at Soda Springs was then presented by Dr. Church, with additional comments being made by BOB GERDEL of the United States Weather Bureau, who is associated with Dr. Church in the experimental work at Soda Springs. W. A. Lang further amplified this discussion by relating some of the experiences of the Southern California Edison Company with various precipitation-gages at Huntington Lake.

During a ten-minute recess following, members gathered in groups relating friendly anecdotes or strolled on the open balcony of the hotel admiring the lights of Berkeley twinkling between raindrops of a welcome storm and avoiding those chummy little nooks where the Army and Navy on leave were entertaining their girl friends.

Following the intermission, Arch Work discussed some different snow-survey equipment being used by his organization in Oregon. These include: (a) Lateral snow-sampler; (b) a steel-pipe climber; (c) a new design for a pack-board and knapsack.

Toastmaster Hall then turned the meeting over to Fred Paget, Chairman of the Executive Committee, for the regular business session of the Conference.

Mr. Paget presented his report as Chairman covering the activities of the Conference during the past year. During the course of his report he announced that inasmuch as he was not in favor of any one man remaining in a position of leadership for a prolonged consecutive period he desired to turn over to a successor or successors his duties as Chairman, Treasurer, and Secretary. He has held the first position during the past four years and the others for the past three years.

W. A. Lang, acting as temporary Treasurer, brought in the Treasurer's report showing assets of $673 and liabilities consisting of a debt to Dr. Church of $350. Mr. Lang stated that he audited Mr. Paget's accounts of the financial affairs of the Conference for the past two years and found them in order. It was moved by Lang and seconded by Arch Work that the Treasurer's report be accepted and also Mr. Lang's audit. The motion was carried.

Arch Work, as a matter of unfinished business, took up the subject of the debt of the Conference to Dr. Church in the amount of $350 which had been due him for money advanced several years ago. In view of the sound financial condition of the Conference he suggested that the loan from Dr. Church should be repaid. Dr. Church responded to the effect that the money was paid not as a loan to the Conference but as a free-will contribution to advance snow-survey science which he conceived as a baby, nurtured as an infant, and guided as a child and youth until it had now attained the stature of strong, virile manhood. He stated that his satisfaction in seeing the Conference grow had well repaid him for what he considered an insignificant outlay of cash for the results achieved and that he would rather the Conference kept the money.

However, it was apparent that the overwhelming sentiment of those present favored repayment to Dr. Church, and Mr. Paget, with the authority of his dual position as Chairman of the Executive Committee and Treasurer, made out a Conference check for $350 and presented it to Dr. Church with a facetious remark about "burning the old mortgage on the 'Church'" followed by remarks in serious vein conveying the gratitude felt by all the Conference to Dr. Church.

Chairman Hall made the suggestion that, with the Conference finances in such good condition, perhaps the Conference might wish to make a donation to the Special Fund which the American Geophysical Union is trying to raise by voluntary subscription. Mr. Paget indicated that he had made a mental note of the suggestion.

As a matter of new business W. A. Lang followed up the idea that a successor be appointed to take over Mr. Paget's multitudinous duties and suggested that in his opinion the logical man for the job was Arch Work of Oregon and made a motion nominating Mr. Work. Mr. Paget pointed out to Mr. Lang that such a motion could not be presented at this meeting as the constitution of the Conference directed and empowered the Executive Committee to select its own Chairman. Mr. Lang then withdrew his original motion and recommended that those at the meeting go on record to the effect that it was the sentiment of this gathering that Mr. Work be selected as successor to Mr. Paget as Chairman of the Executive Committee. This recommendation was seconded and passed unanimously.

A resolution was then passed instructing the Chairman to write a formal letter to Dr. Fleming of the American Geophysical Union and to Professor Veihmeyer, local Chairman of the Section of Hydrology, thanking Professor Veihmeyer for his work in arranging for the joint Berkeley meeting

and expressing the appreciation of the Conference to Dr. Fleming for the continued favors of the American Geophysical Union to the Conference.

The meeting adjourned at 11 p.m.

Fred Paget, Secretary

Annual report of the Chairman of the Executive Committee of the Western Snow-Conference

Meetings--The business of the Snow-Conference during the past year has been more or less routine.

The interest in the Corvallis Meeting was apparent, so much so that the American Geophysical Union of the South Pacific Area again polled their membership as to the advisability of holding a meeting during the winter of 1944 in California. The majority favored it. Your Executive Committee was polled as to their sentiment and most of them were also in favor of such a meeting. This joint meeting is the result.

Officers--In accordance with the desire of the membership expressed in 1942 to forego election of new officers for the duration, your Executive Committee has remained unchanged. The Chairman of the Executive Committee has now held this office during the past four years and he feels that for the good of the Conference another member of the Committee should take over. It is felt that this would not be contrary to the wishes of the membership, even though they have requested the Executive Committee to remain unchanged for the duration, as this is merely a matter of functioning of the Executive Committee to be determined by themselves. The by-laws empower them to select their own Chairman.

Membership--The total paid-up membership of the Conference in 1943 was 194. When the notices for dues of 1944 were sent out early in January two membership application-blanks were also sent to each of the 1943 members for use in case they had a friend or associate who might wish to join. As a result 50 new members have already come in. The paid-up membership for 1944 is now 169 and 75 of the members of 1943 have not yet paid their current dues. Those who continue delinquent up to the end of 1944 are then subject to removal from our rolls, but as of today our membership totals 244.

Transactions--The Transactions of the Corvallis Meeting in June, 1943, were collected and edited by Chairman Work and sent to the American Geophysical Union for publication. The Union continued its past policy of enthusiastic cooperation with the Snow-Conference and printed these Transactions for us on very favorable terms. A copy of the Transactions of 1943 was sent to each of the membership early in January of this year. As each new member is admitted a copy automatically is sent along with his membership-card. Although we have no definite promise it is anticipated that the Union will print the Transactions of this year's meeting as has been done for meetings in the past.

Finances--The financial condition of the Conference has continued to improve. At the time of the Corvallis Meeting we had a balance of $77.66. As of today our assets are $672.94. We still owe Dr. Church for the loan of $350 that has been on our books for some time. Allowing for this debt, our unencumbered balance is now $322.94. This improvement in our financial condition is due in part to the membership dues of $1 and in part to the financial support of water-using organizations interested in furthering the accuracy of the runoff-forecasts obtained from snow-survey information. Some of these organizations are able to make outright contributions to the sustaining fund of the Conference while others accomplish the same general result by purchasing a supply of the Transactions at 50 cents per copy for the use of their organization. A list of the organizations who have either sent in contributions or given us an order for the Transactions is included in the detailed report of the Treasurer.

Although the report of the Treasurer was accepted at the Corvallis Meeting, the last audit of his books was made at the time of the Meeting at the California Institute of Technology in January, 1942. Your Chairman has prevailed upon the good offices of W. A. Lang to audit the books of the Treasurer showing all transactions during the past two years. As a result of his audit Mr. Lang has endorsed the Treasurer's report as being correct.

Prospects--By and large the fact that dependence can be placed on snow-survey information is gaining more and more ground. Most of the water-using organizations are beginning as a matter

of course to accept and rely on snow-survey information as an index of the prospective water-supply. The Snow-Conference is growing in favor. It is becoming easier to secure both moral and financial support for our efforts. The path of the Western Snow-Conference has developed from a winding rocky trail to a broad, paved highway going places.

Fred Paget, Chairman

Treasurer's report

The last report from the Treasurer was made to the Corvallis Meeting on June 16, 1943, by Acting Treasurer Walter E. Johnson.

The report accepted by the Conference showed that the status of the finances at that time was: Assets, balance in bank as of June 10, 1943, $427.66; liabilities, owing to J. E. Church, $350.00. The unencumbered balance was thus $77.66.

Today our financial condition is better. The balance sheet shows: Assets, balance in bank as of February 17, 1944, $491.94, cash on hand $6.00, accounts receivable $175.00, or in total $672.94; liabilities, owing to J. E. Church, $350.00. The unencumbered balance is now $322.94.

Income and expenses since Corvallis Meeting

Receipts				
1943				
July	2	Thirteen memberships	$ 13.00	
Sept.	1	United States Bureau of Reclamation	37.50	
Sept.	1	One membership	1.00	
Dec.	27	Twenty-two memberships	22.00	
Dec.	30	Eleven memberships	11.00	
1944				
Jan.	12	Ten memberships	10.00	
Jan.	15	Thirty-three memberships	33.00	
Jan.	15	Tulare Lake Basin Water Storage District	10.00	
Jan.	17	Twelve memberships	12.00	
Jan.	21	Twenty memberships	20.00	
Jan.	21	Nevada Irrigation District	5.00	
Jan.	21	San Luis Canal Company	10.00	
Jan.	28	Twenty memberships	20.00	
Jan.	28	East Bay Municipal Utility District	10.00	
Jan.	28	Turlock Irrigation District	10.00	
Feb.	1	Twelve memberships	12.00	
Feb.	1	San Joaquin Power Division of Pacific Gas and Electric Co.	10.00	
Feb.	2	One membership	1.00	
Feb.	2	Oregon Agricultural Experiment Station	25.00	
Feb.	2	California Oregon Power Company	25.00	
Feb.	2	Montana Power Company	10.00	
Feb.	7	Southern California Edison Company Limited	25.00	
Feb.	7	Colorado River Water Conservation District	25.00	
Feb.	7	Puget Sound Power and Light Company	5.00	
Feb.	9	Sierra Pacific Power Company	25.00	
Feb.	14	Fourteen memberships	14.00	
Feb.	14	Pacific Gas and Electric Company	25.00	
Feb.	14	Washington Water Power Company	25.00	
Feb.	14	University of Nevada	25.00	$476.50

Disbursements				
1943				
July	3	Stenographer for Corvallis Meeting	$ 3.35	
Nov.	2	Telegram to Dr. Fleming	1.43	
Dec.	13	Postage for circular to 331 old members	5.00	
1944				
Jan.	8	Postage for mailing Transactions of 1943	19.02	
Jan.	8	News Publishing Company for membership cards	9.02	
Jan.	8	American Geophysical Union for Transactions of 1943	318.75	
Jan.	10	Postage for mailing Transactions	5.00	
Jan.	14	Postage for shipments of Transactions	5.00	
Jan.	17	American Geophysical Union for express and addendums	45.65	$412.22
Receipts exceed disbursements by			$ 64.28	
Balance in bank, February 18, 1944			427.66	
Balance in bank, February 18, 1944			$491.94	
Accounts receivable				
Bonneville Power Administration			$ 25.00	
California Division of Water Resources			25.00	
Dominion Water and Power Bureau			5.00	
Montana Agricultural Experiment Station			20.00	
Nevada State Engineer			15.00	
Pacific Power and Light Company			25.00	
San Francisco Public Utilities Commission			10.00	
United States Forest Service			25.00	
Utah State Agricultural College			25.00	$175.00

Fred Paget, Treasurer

Auditor's endorsement

I have audited the accounts of the Treasurer from January 1941 to February 17, 1944, and find them to be correct.

W. A. Lang, Auditor

THE IMPORTANCE OF PRECIPITATION- AND RUNOFF-FORECASTS TO THE OPERATION OF THE PACIFIC SOUTHWEST POWER INTERCHANGE COMMITTEE

In order to meet the greatly increased loads resulting from the war, there was formed early in 1942 the Pacific Southwest Power Interchange Committee, which is composed of representatives of the principal electric generating and distribution systems in the States of California, Arizona, and Nevada. The purpose of this Committee is to coordinate the generating facilities of the various utility systems in order to utilize to the fullest extent all available hydro-generated power and to conserve fuel oil and gas. This Committee has prepared load-resource estimates of the above area for the use of the Office of War Utilities of the War Production Board, and decisions as to the need for additional generating capacity and for the allocation of fuel oil and gas for the generation of electric energy have been and are made by the Office of War Utilities on the basis of these forecasts. Reference is made to an article appearing in the December, 1943, issue of Power Magazine for a more detailed explanation of the function and operation of this Committee.

In view of the critical situation with respect to the supply of fuel oil and gas in the Pacific Coast Area, it is of prime importance to the Committee to have available at the earliest possible time estimates of the probable precipitation and runoff in the watersheds supplying the hydro-generating plants of the utilities in order to obtain the most efficient integration of hydro- and steam-generating facilities. The Power Interchange Committee has an operating subcommittee which makes continuous studies of the load and resources of the various utilities and establishes a general program for the integrated operation of their various generating facilities. This program is revised as often as conditions warrant. It is, therefore, of particular importance that the Committee have available to it at the earliest possible dates any revisions in the estimated precipitation or runoff in the Pacific Coast and Colorado River Basin watersheds. Present indications are that the runoffs in both of these watersheds will be subnormal during the current year which will result in the necessity for substantially increased quantities of fuel oil and/or gas.

The expediting of the latest data and estimates of precipitation and runoff will greatly facilitate the important work of the Power Interchange Committee in its effort to conserve for military use the vitally essential fuel-oil supply of the Pacific Coast Area.

February 16, 1944 N. B. Hinson, Chairman

APPENDIX--RECORD OF ATTENDANCE AT JOINT MEETING OF SECTION OF HYDROLOGY OF THE AMERICAN GEOPHYSICAL UNION AND THE WESTERN SNOW-CONFERENCE, BERKELEY, CALIFORNIA, FEBRUARY 18-19, 1944

[Attendance at snow-surveyors' dinner indicated by (a) and attendance with one guest indicated by (b) following name]

Frank Adams, University of California, Berkeley, California
W. P. Berggren (a), Assistant Professor of Physics, University of California, Davis, California
Tom A. Bither, Engineer, California Corrugated Culvert Company, 7th and Parker Streets, Berkeley, California
Max Bookman, Engineer, U. S. Engineer Office, Sacramento, California
Percy J. Bosanko (b), Hydrographer, Nevada Irrigation District, Grass Valley, California
R. C. Briggs (b), Hydraulic Engineer, U. S Geological Survey, 625 Market Street, San Francisco, California
W. Zev. Bronner, 339 Hilgard Hall, University of California, Berkeley 4, California
F. A. Brooks, Agricultural Engineer, University of California, Davis, California
J. B Brown, Extension Specialist in Irrigation, 304 Giannini Hall, University of California, Berkeley, California
Lloyd N. Brown, Specialist in Soil Conservation, University of California, Berkeley, California
Francis G. Christian (a), Principal Engineer, U. S. Engineer Office, Sacramento, California
J. E Christiansen (a), Irrigation and Drainage Engineer, U. S Regional Salinity Laboratory, Box 672, Riverside, California
J. E. Church (a), Meteorologist, University of Nevada, Reno, Nevada
George D. Clyde, Dean of Engineering, Utah State Agricultural College, Logan, Utah
H. E. Dahman, Junior Hydraulic Engineer, U. S. Geological Survey, 625 Market Street, San Francisco, California
W. A Davis (a), Assistant Editor, Western Construction News, 503 Market Street, San Francisco, California
George G. Devore, Sierra Pacific Power Company, Reno, Nevada
L. D. Doneen, Irrigation Division, University of California, Davis, California
Maurice Donnelly, Soil Conservationist, Soil Conservation Service, c/o Citrus Experiment Station, Riverside, California
Harry C. Dukes (a), Water Master, U. S. Court, 205 Gazette Building, Reno, Nevada
Arthur Dunlop, Senior Engineer, U. S. Engineer Office, Sacramento, California
Blair Eddy (a), Pacific Gas and Electric Company, Colfax, California
Herman J. Fittinger (a), Civil Engineer, U. S. Forest Service, Phelan Building, San Francisco 2, California
Edwin S. Fuller (a), Research Engineer, Los Angeles County Flood Control District, 751 South Figueroa Street, Los Angeles, California
R. W. Gerdel (a), Physicist, U. S. Weather Bureau, Sacramento 9, California
Joseph W. Gross, Engineer, 626 Eye Street, Sacramento, California
L. Standish Hall (b), Hydraulic Engineer, East Bay Municipal Utility District, 512 16th Street, Oakland, California
Ralph C. Hall (a), Entomologist, Forest Insect Laboratory, 341 Giannini Hall, University of California, Berkeley, California
S. T. Harding, Professor of Irrigation, 12 Engineering Building, University of California, Berkeley, California
R. W Hawley (representing William Stava), Railroad Commission of California, State Building, San Francisco, California
A. H. Hendrickson, Pomologist, University of California, Davis, California
Walter J. Herz, Sierra Pacific Power Company, 21 East First Street, Reno, Nevada
Leland K. Hill, Engineer, U. S Engineer Office, Sacramento, California
L. A. Hostetter, Senior Engineer, Water Resources Division, U. S. Army Engineers, 1209 8th Street, Sacramento 8, California
J. W. Johnson, Assistant Professor of Mechanical Engineering, 227 Mechanical Engineering Building, University of California, Berkeley, California

C. N. Johnston, Associate Irrigation Engineer, Irrigation Division, University of California, Davis, California
Henry Karrer (a), Engineer, Patterson Water Company, Patterson, California
C. J. Kraebel, Principal Silviculturist, California Forest and Range Experiment Station, 330 Giannini Hall, Berkeley 4, California
John W. Kuhnel (a), Engineer, U. S. Engineer Office, Sacramento, California
William A. Lang (a), Chief Hydrographer, Southern California Edison Company, 601 West 5th Street, Los Angeles, California
Ray K. Linsley (a), Hydrologic Engineer, U. S. Weather Bureau, 480 Post-Office Building, Sacramento 9, California
T. R. Littlefield, Chief of Water Management, U. S. Forest Service, San Francisco, California
O. C. Magistad, Director, U. S. Regional Salinity Laboratory, Riverside, California
Andrew P. Mazurak, Associate Soil Physicist, University of California, Berkeley, California
H. D. McGlashan, District Engineer, U. S. Geological Survey, 625 Market Street Building, San Francisco, California
T. J. McMahon (a), Water Master, Division of Water Resources, Sacramento, California
Kenneth R. McSwain, Chief Engineer, Merced Irrigation District, 24th and L Streets, Merced, California
Niel F. Meadowcroft, Engineer, Federal Power Commission, Phelan Building, San Francisco, California
Lee O. Murphy (a), Assistant Engineer, Pacific Gas and Electric Company, Room 1310, 245 Market Street, San Francisco, California
M. P. O'Brien, Dean of Engineering, University of California, Berkeley, California
Harry W. Oliver (a), System Dispatcher, Pacific Gas and Electric Company, 245 Market Street, San Francisco, California
Fred Paget (a), Associate Hydraulic Engineer, Division of Water Resources, Sacramento, California
W. J. Parsons, Jr. (a), Engineer, U. S. Engineer Office, Sacramento, California
J. B. Paulson, Jr. (a), U. S. Engineer Office, Sacramento, California
Murvile F. Peightal, Associate Land Appraiser, U. S. Engineers, Sacramento District, Room 234, Post-Office Building, Sacramento, California
Charles W. Petit, U. S. Department of Agriculture, 1268 Shattuck Avenue, Berkeley, California
Arthur F. Pillsbury (a), Assistant Professor of Irrigation, University of California, Los Angeles 24, California
Anthony J. Polos, Assistant Hydraulic Engineer, U. S. Weather Bureau, 460 Flood Building, San Francisco 2, California
Harry L. Potts (a), Water Rights Engineer, Board of Water Commissioners, Denver, Colorado
P. B. Rowe (a), Silviculturist, California Forest and Range Experiment Station, 33O Giannini Hall, Berkeley, California
G H. Russell, Senior Engineer Appraiser, Farm Credit Administration, Federal Land Bank, Berkeley, California
Carl E. Schneider (a), Associate Engineer, U. S. Engineer Office, Sacramento, California
A. C Showman, Senior Engineer, U. S. Engineering Department, Sacramento, California
J. D. Sinclair, Senior Silviculturist, California Forest and Range Experiment Station, Glendora, California
C. W. Sopp, Assistant Chief Engineer and General Manager, Pasadena Water Department, 319 City Hall, Pasadena 1, California
Harlowe M. Stafford (a), Senior Hydraulic Engineer, Water Resources Branch, U. S. Geological Survey, 421 Federal U. S. Post-Office and Court House, Los Angeles 12, California
R. Earl Storie (a), Soil Technologist, 320 Hilgard Hall, University of California, Berkeley, California
Garfield Stubblefield, Engineer, Bureau of Reclamation, 407 California Fruit Building, Sacramento, California
Forrest F. Varney (a), Senior Engineer, U. S. Engineer Office, Sacramento, California
E. W. Vaughan, Senior Engineer, Sacramento District, Engineer Office, Wright Building, Sacramento, California
Fred M. Veatch (a), District Engineer, U. S. Geological Survey, 207 Federal Building, Tacoma, Washington
F. J Veihmeyer, Division of Irrigation, University of California, Davis, California
R. D. Waterhouse (a), Engineer, National Park Service, 601 Sheldon Building, San Francisco 5, California
Walter W. Weir, Drainage Engineer, 320 Hilgard Hall, University of California, Berkeley, California
A. J. Whiteside, Assistant Civil Engineer, Soil Conservation Service, Walnut Creek, California
Robert L. Wing, Associate Hydraulic Engineer, State Division of Water Resources, Public Works Building, Sacramento, California

L. R. Wohletz, Associate Soil Scientist, Soil Conservation Service, 2168 Shattuck Avenue, Berkeley, California
R. A. Work (b), Irrigation Engineer, U. S. Soil Conservation Service and Oregon Agricultural Experiment Station, P. O. Box 1149, Medford, Oregon
Roy Wray, Division of Irrigation, University of California, Davis, California

EFFECT OF HIGH WATER-TABLE IN EXAGGERATING STREAM-FLOW: FURTHER ANALYSIS OF UNUSUAL YEAR 1942-43 AND ANALYSIS FOR YEAR 1943-44 ON UPPER HUMBOLDT RIVER, NEVADA

J. E. Church and H. P. Boardman

Year 1942-43--The water-year of 1942-43, because of the normality of its weather features, has provided further opportunity to confirm the potency of high water-table on the runoff of the upper Humboldt and determine its relative effect.

The only questionable factor is that of precipitation and snow-cover. The former for November to February was 137.6 per cent of normal and the snow-cover for March 1 was 91.5 per cent of normal but at low levels only 42.1 per cent. Fortunately in the central Sierra, with almost identical conditions of precipitation and snow-cover, the percentage of runoff was closely similar to that of the snow at the higher levels. Therefore, for purposes of comparison the snow-cover in the Humboldt Basin may be considered reliable and its effectiveness as approximating 91.5 per cent of its normal.

The precipitation during March to July, the period of runoff, was near or slightly below normal except for the month of June when the precipitation was 100 to 240 per cent in excess of normal.

On the other hand, at Elko and Lamoille, except for excess temperatures of +4°.8 and +7°.4 F, respectively, in April, the temperature was at or below normal and in June when the precipitation was heaviest the temperature-departure was lowest or respectively -5°.6 and -5°.0 F at the two stations.

The winter runoff at Palisade was 125,330 acre-feet or 435.2 per cent of normal, an unprecedented occurrence, but a part of this was flood-water in January and February.

The wells in Humboldt and Lamoille valleys in March were higher than for previous years of record, except 1942 in the former. More exactly, in Humboldt Valley the wells were 1.65 feet higher than the group-normal of 11.62 feet (below the surface of the ground) and in Lamoille Valley were 0.84 foot higher than their group-normal of 4.24 feet.

This excess, intensified probably by the heavy priming of the soil in the floods of January and February, created a total runoff for March to July of 216.2 per cent of normal or 125 per cent of normal above the 91.5 per cent of the snow-cover.

On the other hand, South Fork (near Elko) where it enters the main Humboldt failed to be affected by the high water-table noted in the alluvial valley of the main stream and flowed at approximately the percentage of normal represented by the snow-cover (snow-cover 70.1, runoff 90.0).

Though not earlier realized, this harmony between snow-cover and runoff is understandable, for South Fork has a steep gradient and quick return-flow in its V-shape valley. Fortunately the record on South Fork is based on a normal of 38 years, the station is rated as good by the United States Geological Survey, and the record for 1942-43 is continuous.

The records of three neighboring streams, upper South Fork, Lamoille Creek, and Starr Creek, where they leave the foothills of the high Ruby Mountains, show the same trend despite their fragmentary condition caused by withdrawal of the State Hydrographer into War Service. These records as interpolated in per cent of normal for missing months are as follows:

	Snow-cover, March 1	Runoff, April to July
South Fork (Boltons)	70.1	114.6 estimated
Lamoille Creek (near Lamoille)	97.9	121.2 estimated
Starr Creek	97.4	121.8 estimated
Main Humboldt (Palisade)	91.4	193.0

Fig. 1--Relief map of Humboldt Drainage-Area.

Because of lack of records, the seasonal period of the tributaries except lower South Fork (near Elko) is confined to April to July. During this period the main Humboldt flowed 193.0 per cent as contrasted with 216.2 per cent for the period of March to July.

Since upper South Fork (at Boltons) has no alluvial valley above it and scant water-table, its percentage of runoff should be even less than on the lower South Fork (near Elko). Both are the self-same stream except for tributaries entering below. By the new normal of 44,000 acre-feet (mean of the six years, 1937-42) the percentage is 114.6 per cent. Similarly by a new six-year normal on the other streams compared, the trends are visible.

At the lower end of Lamoille Valley, where the water-table has a wide fluctuation, and in Marys River Basin, known for its gentle gradient and continuous dams, the runoff tends upward toward that of the main Humboldt in the former and far exceeds it in the latter.

Table 1--Monthly phases of runoff with precipitation and temperature

Period	Snow-cover	Precip. (Lamoille only)	Temp. departure	Runoff
	pct	pct	°F	pct
November-February	74.1	70.3	-2.0	63.7
March	. . .	47.3	-5.0	92
April	. . .	262.3	-5.0	87
May	. . .	50.7	-1.0	108
June	. . .	349.0	-7.2	150
July 1-22	. . .	0.0	. . .	181.2
March-July	. . .	131.2	. . .	119.7

The percentages for April to July are as follows: Lower Lamoille Creek (McIntyres), 140.1; Marys River (Cabin Field), 279.3; Main Humboldt River (Palisade), 193.0.

Since the gage at McIntyres was bypassed by much water in the higher stages of Lamoille Creek, the percentage of runoff must be considerably higher than recorded.

Lamoille Creek flows quickly and only a relatively short distance from its mountain rim to the south, while Marys River flows far and sluggishly from its mountain basin in the far north.

If more and better records were available, it would be possible to trace the influence of the ground water-table up the various finger-basins of the Humboldt which comprise its source. But plainly this influence does not extend above the canyon-throats nor up the V-shape valleys where the gradient is steep.

The relief map of Figure 1 presents the data visually.

Year 1943-44--The flow of the main Humboldt for the current year appears to confirm the effect of the water-table. On March 1 and April 1 the water-table was still slightly above normal and the winter runoff was 63.7 per cent of normal, despite a minus departure of 9° to 2°F in January to February.

The snow-cover in the basin averaged 74.1 per cent (65.4 on northern feeders and 82.3 on southern). On the assumption that the excess effect of the water-table should be at least 20 per cent, the forecast of runoff at Palisade for March to July was raised to 95 per cent.

The runoff near the end of this period (July 22) has actually reached 120 per cent or 45 per cent above the average percentage of the snow-cover.

The temperature-departure for March-April was -5°F and has probably been nearly as low in May-June. The precipitation during runoff was greatly deficient in March, May, and July but greatly in excess in April and June. For the period of March-June, when most effective, it totaled 143.0 per cent of normal. The monthly phases of runoff with precipitation and temperature are shown in Table 1.

The low temperature has delayed the melting and caused it to increase toward the close of the period. At the end of May the precipitation was only 13.5 per cent in excess of normal. The

Table 2--Mean departures (in feet) from normal in two series of wells in Lamoille and Humboldt valleys and corresponding winter flow of main Humboldt (in percentage of normal)
[Plus (+) indicates rising water-table]

Item	Year									
	1935	1936	1937	1938	1939	1940	1941	1942	1943	1944
Wells' depth to water										
Lamoille Valley (mean 7 wells, 4.24 ft, March 1)	-0.79	+0.52	+0.67	-0.26	+0.32	-0.26	-1.46	+0.44	+0.84	+0.10
Humboldt Valley (mean 7 wells, 11.62 ft, April 1)	. . . .	. . . .	. . . .	. . . .	. . . .	. . . .	-1.28	+2.43	+1.65	+3.47[a]
Runoff, Humboldt River at Palisade (Nov.-Dec.)	30.5	46.4	49.0	44.6	76.2	71.0	69.2	209.5	435.2	89.8

[a] Five wells.

Table 3--Principal elements associated with stream-flow

Year	Month	Departures based on Elko, Wells, and Lamoille		Palisade winter runoff	Wells' departure from normal			Runoff Palisade March-July	Humboldt Basin Snow-survey	Precipitation, March-July, average of Elko, Wells, and Lamoille	
		Temperature [a]	Precipitation	Nov.-Dec.	Humboldt Valley wells April 1	Lamoille Valley Wells, March 1 Deep	Lamoille Valley Wells, March 1 Shallow			Pct normal	Departure
		°F	in	pct[b]	ft	ft	ft	pct[b]	pct[b]	pct[b]	in
1934-35	Nov.	+3.1	+0.96	31	....	-5.79	-0.33	69	74	113	+0.71
	Dec.		-0.25	..	....	....	....	..	..	...	....
	Jan.		-0.49	..	....	....	....	..	..	...	....
	Feb.		-0.68	..	....	....	....	..	..	...	....
Mean			-0.46	..	....	....	....	..	..	...	....
1935-36	Nov.	-3.9	-0.49	46	....	-2.53	+0.42	117	135	112	+0.60
	Dec.		-0.09	..	....	....	....	..	..	...	....
	Jan.		+0.38	..	....	....	....	..	..	...	....
	Feb.		+1.10	..	....	....	....	..	..	...	....
Mean			+0.90	..	....	....	....	..	..	...	....
1936-37	Nov.		-0.79	49	....	+0.11	+0.71	80	78	100	-0.01
	Dec.		+0.56	..	....	....	....	..	..	...	....
	Jan.	-15.6	-0.02	..	....	....	....	..	..	...	....
	Feb.		-0.08	..	....	....	....	..	..	...	....
Mean			-0.33	..	....	....	....	..	..	...	....
1937-38	Nov.	+3.7	+0.22	45	-0.95	-1.30	+0.43	98	63	144	+2.41
	Dec.		+0.02	..	....	....	....	..	..	...	....
	Jan.	+4.2	-0.32	..	....	....	....	..	..	...	....
	Feb.		-0.64	..	....	....	....	..	..	...	....
Mean			-0.72	..	....	....	....	..	..	...	....
1938-39	Nov.	-5.4	-0.09	76	+0.11	+1.45	-0.71	68	69	96	-0.21
	Dec.	+5.1	-0.94	..	....	....	....	..	..	...	....
	Jan.		-0.70	..	....	....	....	..	..	...	....
	Feb.	-9.8	-0.90	..	....	....	....	..	..	...	....
Mean			-2.63	..	....	....	....	..	..	...	....
1939-40	Nov.	+3.5	-0.53	71	-1.60	+2.98	-0.36	61	56	107	+0.37
	Dec.	+8.6	-0.92	..	....	....	....	..	..	...	....
	Jan.	+3.6	+0.45	..	....	....	....	..	..	...	....
	Feb.	+5.4	+0.10	..	....	....	....	..	..	...	....
Mean			-0.90	..	....	....	....	..	..	...	....
1940-41	Nov.		-0.23	67	-1.54	-3.73	-0.94	108	71	176	+4.16
	Dec.	+4.5	+0.37	..	....	....	....	..	..	...	....
	Jan.		-0.51	..	....	....	....	..	..	...	....
	Feb.	+4.3	-0.35	..	....	....	....	..	..	...	....
Mean			-0.72	..	....	....	....	..	..	...	....
1941-42	Nov.		+1.27	210	+2.46	+2.63	+0.38	230	90	112	+0.67
	Dec.	+3.9	+0.84	..	....	....	....	..	..	...	....
	Jan.		+0.24	..	....	....	....	..	..	...	....
	Feb.	-6.3	0.00	..	....	....	....	..	..	...	....
Mean			+2.35								
1942-43	Nov.		+1.93	446	+1.67	+4.68	+0.66	214	91	126	+1.40
	Dec.	+5.9	+0.70	..	....	....	....	..	..	...	....
	Jan.	+4.6	+0.82	..	....	....	....	..	..	...	....
	Feb.		-0.23	..	....	....	....	..	..	...	....
Mean			+3.22	..	....	....	....	..	..	...	....
1943-44	Nov.		-0.22	90	....	+1 43	+0 14	..	74	...	....
	Dec.		-0.48	..	....	....	....	..	..	...	....
	Jan.	-7.5	-0.34	..	....	....	....	..	..	...	....
	Feb.		-0.49	..	....	....	....	..	..	...	....
Mean			-1.53	..	....	....	....	..	..	...	....

[a] Temperature-departure from normal is shown only for those months when its average for the three stations Elko, Lamoille, and Wells (or for Elko and Lamoille for 1934-38) was 3°0 or greater Temperature-records for Wells are lacking for years 1934-38. [b] Percentage of normal.

heavy precipitation of June increased the excess to 43.0 per cent and accentuated the peak of the flow.

This accentuation, on basis of earlier measurement in June, 1913, should increase the monthly flow 45 per cent but the flow during March to July only 12.8 per cent. The excess flow in July will be approximately eight per cent as applied to the flow, making the total excess due to rain approximately 20 per cent. The excess due to high water-table would therefore be 25 per cent or five per cent more than forecast.

The behavior of the tributaries has not yet been computed, except for Starr Creek, which with a snow-cover of 84.4 per cent of normal had a runoff (April to July) of 104.5 per cent. This runoff, if corrected for excess rain (20 per cent), would be 84.5 per cent or that of the snow-cover.

Winter runoff versus water-table as index of base-flow--The winter runoff should at minimum represent the effect of the water-table but at maximum can be the effect of high temperature and rain.

Table 2 of mean departures (in feet) from normal in two series of wells in Lamoille and Humboldt valleys and the corresponding winter flow of the main Humboldt (in percentage of normal, November to February) shows the diversity that can occur. Only in the last three years do the water-table and winter runoff run at all parallel.

To provide a complete picture of all principal elements associated in stream-flow--such as winter temperature, precipitation, and runoff, spring water-table and snow-cover, summer runoff and precipitation--Table 3 has been prepared by the junior author.

Nevada Agricultural Experiment Station,
Reno, Nevada

Discussion--The following correspondence was elicited by the paper on "Three unusual runoff-years in the Humboldt Basin, Nevada, 1940-41, 1941-42, and 1942-43" by J. E. Church and H. P. Boardman [Trans. Amer. Geophys. Union, pp. 67-71, 1943], and is so suggestive that it is appended to the present paper to which it also belongs. The possibilities of winter or March runoff in forecasting have been mentioned in the forecast of the Humboldt for 1944.

W. G HOYT: "Never having made any forecast of runoff based on snow-measurements and being especially unfamiliar with methods used in Nevada, it is perhaps presumptuous on my part to enter into a discussion with you concerning your joint paper with Professor Boardman published in the American Geophysical Union Transactions, Part 3, 1943.

"It appears from your discussion that the unusually wide divergence between the actual runoff and the forecast runoff during the spring of 1942 has emphasized the factors of soil-moisture and ground-water levels that have 'previously seemed subordinate to those of snow-cover and precipitation.' By making comparisons between the actual flow during the spring of 1943 and the forecasted flow, you arrive at the conclusion that roughly 50,000 acre-feet of the difference between the forecast and the observed runoff can be attributed to excess water associated with the flood of April, 1942, and roughly 250,000 acre-feet to the effect of high ground-water table. During the spring of 1943 ground-water conditions were apparently similar to those during the spring of 1942 and by adding 250,000 acre-feet to the forecasted runoff from snow you arrived at a total forecast under normal conditions of roughly 400,000 acre-feet and possible maximum of 430,000 acre-feet for the total runoff March through July, 1943. These forecasts agree closely with the actual runoff of 443,000 acre-feet.

"The question I raise is the extent to which you have made correlations between factors other than snowfall and precipitation in arriving at your forecast. If it is assumed that 250,000 acre-feet represents the maximum effect of high soil-moisture content and high ground-water in the Humboldt River Basin above Palisades, what amount would represent normal or minimum conditions?

"The point has long been stressed that in the absence of detailed observations of soil-moisture and ground-water conditions, stream-flow itself is a satisfactory index of natural storage-conditions within a basin and that through a study of stream-flow alone it is possible to arrive at rather definite conclusions of the effect of antecedent conditions on the amount of snow or rain which will be translated into stream-flow. To the extent that this is so, it would seem that the rain, snow, and temperature elements could be superimposed on the correlations to arrive at the most probable answer concerning future runoff. For example, we may be correct in assuming that to a very large extent the flow of Humboldt River during October is more dependent on antecedent conditions than on either snow-melt or precipitation during October. If this assumption is correct, there should be a good correlation between antecedent conditions and October flow. If we take the flow at the end of September as a measure of antecedent conditions, we find a very high degree of correlation

between the October flow and this index. In fact, based on this index alone with no consideration given to meteorological conditions an outlook for the October runoff could be made which would deviate ten per cent or less from the observed October runoff for half of the time. During the spring and early summer months the problem is, of course, complicated by the fact that there may be a closer relation between runoff and meteorological factors than there is between runoff and natural storage-conditions as measured by the deficiency or excess of soil-moisture and ground-water.

"During the period 1920-43 the total runoff of the Humboldt River at Palisade has varied from a minimum of about 10,000 acre-feet in 1934 to a maximum of 554,000 acre-feet in 1921 with an average of about 195,000 and a normal value as measured by the median of about 155,000. (Incidentally, it is noticed that in your discussions you use arithmetical average as a normal rather than the median value. In other words, due to the fact that a relatively few high years raise the average, actually the flow reaches or exceeds your normal for considerably less than half the time. Is not a normal based on a median value more significant?) The question arises as to how much of the variation between seasonal runoff of 10,000 acre-feet and 554,000 acre-feet results from differences in snow-melt and rainfall and how much from natural storage-conditions as reflected by soil-moisture and ground-water. I find that using the flow during the last of March as an index and disregarding entirely the snow- and rain-factors, an outlook could have been made of the total runoff for the five months March through October which would have deviated 32 per cent or less from observed runoff for half of the time. This outlook, as of April 1, would correspond with the time of the making of your first preliminary statements concerning flow-conditions in Nevada. If the flow during the latter part of April is taken as an index, and disregarding again all meteorological conditions, an outlook could have been made of the five months' flow which would have deviated but 23 per cent or less from the actual flow for half of the time. This outlook would correspond in time to your final forecast made early in May when the runoff for March and April are known. If the outlook, as of May 1, is related to the prospective flow for the months of May, June, and July only and the known March and April flow added, the total outlook would have deviated but 22 per cent or less for half the time. If an outlook had been made at the beginning of each month, March to July, using an index based on the flow during the latter part of the previous month, the combined monthly outlooks March to July would have deviated but 17 per cent from the actual observed flow March to July. In other words, it seems that antecedent conditions reflect the amount of snow-melt and precipitation that will be translated into runoff; otherwise the correlations such as have been outlined and which afford a measure of the effect would not have been obtained.

"We have not had time to make what might be considered anywhere near an exhaustive study. Such correlations as have been made of the flow of various index-streams, however, confirm our impression that stream-flow records can be used as a measure of antecedent conditions and through their use there would seem to be a possibility to work out correlations whereby the accuracy of forecasts based on snow-melt and precipitation could be increased. It may well be that you have analyzed long-time ground-water observations and have correction-factors established whereby you can adjust your forecasts based on snow and rain. Such correlations, if any, however, are not outlined in your interesting and instructing paper."

ACCURACY OF FORECASTS OF RUNOFF FOR CENTRAL SIERRA EASTERN SLOPE, 1942 AND 1943

H. P. Boardman

The runoff of the streams in this region for the 1942 season was very much greater than was expected, as is shown in Table 1.

The reason was an unusually high April-May precipitation. United States Weather Bureau records for those two months show the following results: Truckee, Tahoe City, and Marlette Lake had 345, 186, and 208 per cent of normal, respectively; the average was 229 per cent of normal for the following ten stations: Sierraville; Bowman Dam; Lake Spaulding; Blue Canyon; Soda Springs; Twin Lakes; Tamarack (Blue Lakes); Lake Eleanor; Hetch Hetchy; and Gem Lake. Quantitatively the excess above normal ranged from 2.84 inches at Tahoe City and 2.80 inches at Gem Lake (which is 13 miles southeast of Tioga Pass, at altitude 9,000 feet) to 11.66 inches at Blue Canyon and 12.64 inches at Lake Spaulding. This excess was 6.66 inches at Soda Springs and 8.42 inches at Tamarack (Blue Lakes). Most of the April excess fell on snow-blanket in both high and low altitudes and the May excess on snow-blanket in the high altitudes so that a large part of the April-May excess was directly effective in increasing the snow-water content.

Approximate estimates give assurance that this excess spring precipitation was sufficient to easily account for the increase of runoff above that indicated by the April 1 snow-surveys.

Table 1--Forecasts of runoff and results, Central Sierra eastern slope, 1942 and 1943

Basin or stream	Normals	1942				1943			
		Forecast		Actual results		Forecast		Actual results	
		Pct Normal	Amount	Amount	Pct Normal	Pct Normal	Amount	Amount	Pct Normal
	ft		ft	ft			ft	ft	
Rise of Tahoe[a], April 1 to high water	1.68	95.2	1.60	2.17	129.2	101.2	1.70	1.67	98.4
Tahoe maximum elevation[a]	...	Jul 15	6229.45	6230.02	Jul 26	....	6229.90	6229.82	Jul 13
Tahoe maximum controlled elevation	...	....	6229.10	6229.01	Jul 14-15	....	6229.10	6229.02	Jul 13
	ac-ft		ac-ft	ac-ft			ac-ft	ac-ft	ac-ft
Truckee River, exclusive of Tahoe	325,700	87.5	285,000	341,300	104.8	92.1	300,000	297,830	91.4
Carson River at Ft.Churchill	230,000	66.1	152,000	252,800	109.9	100	230,000	234,900	102.1
West Walker near Chris Flat	191,200	90.0	172,000	192,000	100.8	91.0	174,000	175,650	91.9
East Walker below Bridgeport Dam	73,000	83.6	61,000	93,500	128.1	82.2	60,000	82,330	112.8

[a] Assuming gates closed; no outflow.

As shown in Table 1, the Tahoe outlet-gates were so regulated as to keep the actual maximum elevation below the agreed upper limit and yet the difference, 0.09 foot, represented about 11,000 acre-feet of lost storage. However, evaporation from the lake probably takes away nearly 400,000 acre-feet annually.

As Table 1 will show, the actual resulting runoff for 1943 checked within less than five per cent of normal with the predictions made in our Forecast Bulletin published last April, with the exception of the East Walker River, where actual results exceeded the forecast by a relatively large amount. Two important snow-courses in the East Walker Basin, Center Mountain and Buckeye Forks, were not surveyed in 1943 and very likely too low an estimate was made of the probable water-equivalent on those courses when working up the forecast. Also perhaps the unusually high precipitation of November, 1942, raised the water-table in Bridgeport Valley enough to materially decrease the usual spring loss due to percolation and evaporation in that valley.

Due to the high level of Lake Tahoe carried over from the previous year it was necessary to open the outlet-gates and release large quantities of water to prevent a rise above the stipulated maximum elevation of 6229.10.

Nevada Cooperative Snow-Surveys,
Reno, Nevada

ACCURACY OF 1942 OREGON WATER-SUPPLY FORECASTS

Wilfrid T. Frost

Stream-flow throughout Oregon in 1942 exceeded the amount forecast except in one small area on the east slope of the Cascades near Bend. This behavior agreed with the distribution of precipitation during April to May. Since all forecasts are based on expectation of normal temperature and precipitation during runoff, the effect of State-wide, April to May precipitation 60 per cent above normal was notable. Precipitation by districts, expressed as per cent above normal, follows: Southeastern, 59; South-central, 86; North-central, 19; Columbia River, 43; Wallowa Mountains, 79; Blue Mountains, 65; Southern, 75; Willamette Valley, 65.

Precipitation 153 per cent normal during April to June in the Rogue River Basin resulted in stream-flow 23 per cent greater than forecast. Precipitation 158 per cent normal in the Upper Klamath Basin resulted in an inflow to Upper Klamath Lake 26 per cent greater than forecast. A discharge of 139 per cent of the amount forecast on the Owyhee River was attributed to precipitation 171 per cent normal and the East Fork of the Wallowa River flowed 141 per cent of the forecast due to a precipitation 161 per cent normal. Similarly, precipitation 176 per cent normal caused a flow 143 per cent of the forecast on the Umatilla River at Pendleton, etc.

In the Bend Area precipitation for April to June was about 80 per cent normal. Flow of Tumalo Creek for April to September was 90 per cent of the amount forecast.

The water-supply forecasts for 1942 have been verified to the extent that 41 per cent were 90 per cent correct or better and 71 per cent were 80 per cent correct or better. Ten per cent were 95 per cent correct or better.

[Note: Due to lack of man power the stream-flow records in Oregon for 1943 have not yet been worked up. Comparisons with forecasts for 1943 cannot be made.]

U. S Soil Conservation Service,
Medford, Oregon

ACCURACY OF FORECASTS OF RUNOFF FOR COLUMBIA, KOOTENAY, AND OKANAGAN BASINS AND THE COASTAL BELT ADJACENT TO VANCOUVER FOR 1942

S. H. Frame

The rainfall from April to July, 1942, for the southern interior portions of the Province was very heavy. Observations at ten representative stations in the Kootenay and Columbia basins show that the total precipitation for these months was 60 per cent above the average, while in the Okanagan it was 100 per cent above. In the Coastal Area it approached nearer the normal by being 18 per cent above.

Coastal summer temperatures were slightly above the average while those in the Okanagan were slightly below. The Kootenay and Columbia basins had a normal temperature for the period April to July, the 26-year average being 53°.

The runoff of the Kootenay River at Glade, from April to August, was 61 per cent over that of 1941, while that of the Columbia at Trail, for the same period, was 23 per cent over 1941.

The foregoing facts are given to show why the forecasting from the water-content of the snow-cover was not more closely reflected in the runoff.

Table 1 gives the summer precipitation and temperature in per cent of normal. Table 2 gives a summary showing the forecasted and actual runoff in acre-feet, with percentages of error from the actual.

Coastal Area--At the end of March the snow-cover at elevations below 1,500 feet was very light, while at elevations between 2,600 and 3,800 feet it approached more nearly to the average depth. The forecast from the snow in the Powell River Area expressed in per cent of the average runoff from Powell Lake during April to July was 101.3, comparing favorably with the actual runoff of 111.1 per cent. At lower elevations in the Vancouver and Stave Lake areas the amount of snow on the ground was negligible and, consequently, of no forecasting value. The discharge of the Stave River during April to July was 12 per cent below the average, but 16 per cent above that of 1941. The flow of the Capilano River for the same period was 14 per cent above that of 1941.

Okanagan Basin--The forecast for this Basin was for 72 per cent of the average runoff during April to July; the actual, which was 129 per cent more than last year, was 161 per cent of the average.

East Kootenay--The prediction for the Elk and Kootenay (at Wardner) rivers in this Area was for 75 per cent of the average runoff during April to August. The actual runoff was 120 per cent of the average and 93 per cent more than that of 1941.

Table 1--Precipitation and temperature in percentage of normal

Station	April to July, 1942 Precipitation		Station	April to July, 1942 Temperature	
	Average	Per cent average		Normal	Per cent normal
	in				
			Coastal		
Powell River	7.28	124	Powell River	57	102
Lois River	11.99	119	. . . . .	. .	. . .
Capilano	20.56	103	Vancouver	57	102
Stave Falls	15.95	143	Stave Falls	57	102
Stave Lake	29.29	106	Stave Lake	58	98
Hope	9.15	113	Hope	59	100
. . . . .	. . . .	. . .	Agassiz	58	103
			Interior		
McCulloch	8.51	206	McCulloch	48	100
Osprey Lake	4.90	194	Osprey Lake	51	94
Field	7.53	117	. . . . .	. .	. . .
Glacier	10.73	128	Glacier	48	100
Cranberry Lake	5.18	172	. . . . .	. .	. . .
Revelstoke	7.88	148	Revelstoke	56	102
Nakusp	8.24	176	. . . . .	. .	. . .
New Denver	7.79	140	. . . . .	. .	. . .
Deer Park	4.82	193	. . . . .	. .	. . .
Fernie	9.39	181	Fernie	52	98
Kaslo	6.17	158	Kaslo	55	96
Nelson	7.62	190	Nelson	56	102
Blue River	11.37	. . .	. . . . .	. .	. . .

Table 2--Forecast and actual runoff, 1942

Main river-basin	Tributary basin	Stream Name	Stream At	No. courses involved	Runoff Forecast	Pct normal	Actual	Pct normal	Error pct actual
					ac-ft		ac-ft		
				Coastal					
Fraser	Stave	Stave	Stave Falls	3	. . . . .	. . . .	901,000	88.0	. . . .
Powell	. . . . .	Powell	Powell Lake	3	884,300	101.7	795,700	91.5	+11.1
				Interior					
Columbia	Kootenay	Lardeau	Gerrard	1	344,300	71.9	466,700	97.8	-26.2
Columbia	Kootenay	Duncan	Howser	1	852,600	48.5	1,602,000	91.8	-46.8
Columbia	Kootenay	Elk	Elko	2	902,000	77.9	1,440,000	124.4	-37.4
Columbia	Kootenay	Slocan	Crescent	1	1,088,000	65.3	1,536,000	93.8	-29.2
Columbia	Kootenay	Kootenay	Wardner	3	2,765,000	71.7	4,554,000	96.3	-39.3
Columbia	Kootenay	Kootenay	Glade	5	9,274,000	60.6	16,373,000	106.7	-43.4
Columbia	. . . . .	Columbia	Golden	3	1,558,000	74.2	2,022,000	96.4	-22.9
Columbia	. . . . .	Columbia	Revelstoke	6	10,944,000	61.5	15,864,000	89.5	-31.0
Columbia	. . . . .	Columbia	Trail	14	23,612,000	67.3	35,150,000	82.4	-22.7
Okanagan	Okanagan	Okanagan	Penticton	5	206,100	72.0	474,200	160.6	-56.5

North Kootenay Area--The Lardeau River was predicted to run 72 per cent of its normal April to August runoff of 478,800 acre-feet and the Duncan River, for the same period, 48 per cent of its normal of 1,758,000 acre-feet. The forecasts were too low by 26 and 47 per cent, respectively. The combined actual runoff from these two streams was 92 per cent of normal.

West Kootenay and Arrow Lakes Area--The actual runoff of the Kootenay River at Glade for the months of April to August was greater than the average flow by 6.7 per cent and greater than last year's by 61 per cent. The forecast for the same period was for 61 per cent of average. The Slocan River forecast of 65 per cent of average was 29 per cent below the actual.

Columbia Basin--The water-content in the snow-cover gave a forecast of 68 per cent of normal for the runoff of this Basin during April to August. The actual runoff was 89 per cent of the same normal which is 21 per cent more than the prediction. This year's runoff for the same period was slightly above last year's at Revelstoke, and at Golden and Trail 32 and 23 per cent above, respectively.

Department of Lands, Water Rights Branch,
Victoria, B. C.

ACCURACY OF FORECASTS OF RUNOFF FOR COLUMBIA, KOOTENAY, AND OKANAGAN BASINS AND THE COASTAL BELT ADJACENT TO VANCOUVER FOR 1943

S. H. Frame

As given in the end-of-March snow-survey report, the water-content of the snow was very much greater than that of the previous year, and from 15 per cent greater than average in the Okanagan Area to 38 per cent greater than average in the Kootenay-Columbia Basin. (See p. 182 for map of Snow-Survey System.)

It was feared that, with this excess amount of potential runoff stored in the snow there would follow a possible flood-danger; however, in the interior areas this was averted by the following facts: The rainfall from April to August was that of a normal year, it being only four per cent above average. The temperature for this rainfall-period was two per cent below normal. The April runoff was comparatively high, giving a lesser amount to run off later. The decidedly cool weather during May caused a gradual runoff which was considerably below the month's average. In June, owing to continued cool weather, the runoff was still being taken care of gradually. This month is usually the beginning of peak-discharges, but owing to the foregoing conditions, the accumulation of peaks had been kept down, even though the July runoff was above the average through warmer weather conditions and delayed runoff from the cooler previous months. August was not an excessively hot month and precipitation, though slightly above normal, did not swell the remaining runoff from the snow-cover to other than that of an August average.

Table 1--Precipitation and temperature in percentage of normal

Station	April to July, 1943				
	Precipitation		Temperature		
	Average	Per cent average	Station	Normal	Per cent normal
	in		Coastal		
Powell River	7.31	112	Powell River	57	100
Lois River	12.09	109	. . . . .	..	...
Capilano	20.43	83	Vancouver	57	100
Stave Falls	15.96	102	Stave Falls	57	98
Stave Lake	28.86	90	Stave Lake	57	96
Hope	9.38	182	Hope	59	97
. . . . .	....	...	Agassiz	58	98
			Interior		
McCulloch	8.49	94	McCulloch	48	98
Osprey Lake	4.92	107	Osprey Lake	50	96
Field	9.49	100	. . . . .	..	...
Glacier	13.26	125	Glacier	49	96
Cranberry Lake	6.41	123	Cranberry Lake	54	96
Revelstoke	9.55	115	Revelstoke	58	102
New Denver	9.21	71	. . . . .	..	...
Deer Park	5.86	91	. . . . .	..	...
Fernie	10.93	113	Fernie	54	96
Kaslo	7.35	88	Kaslo	56	96
Nelson	8.95	115	Nelson	56	105
Blue River	13.40	103	. . . . .	..	...

From Field to Blue River, in Table 1, the period is from April to August.

Table 2--Forecast and actual runoff, 1943

Main river-basin	Tributary basin	Stream: Name	Stream: At	No. courses involved	Runoff: Forecast	Runoff: Pct normal	Runoff: Actual	Runoff: Error pct actual
					ac-ft		ac-ft	
				Coastal				
Fraser	Stave	Stave	Stave Falls	3	.....	....	1,049,000	....
Powell	.....	Powell	Powell Lake	3	.....	....	941,300	....
				Interior				
Columbia	Kootenay	Lardeau	Gerrard	1	528,700	110.8	507,500	+ 4.2
Columbia	Kootenay	Duncan	Howser	1	2,179,000	124.8	1,583,000	+37.7
Columbia	Kootenay	Elk	Elko	2	1,575,000	134.7	1,283,000	+22.8
Columbia	Kootenay	Slocan	Crescent	1	2,393,000	146.2	1,603,600	+49.2
Columbia	Kootenay	Kootenay	Wardner	3	4,550,000	117.2	3,247,300	+40.1
Columbia	Kootenay	Kootenay	Glade	3	18,731,000	122.1	17,860,000	+ 4.8
Columbia	.....	Columbia	Golden	3	2,434,000	116.0	1,929,000	+26.2
Columbia	.....	Columbia	Revelstoke	6	18,384,000	104.0	15,062,000	+22.0
Columbia	.....	Columbia	Trail	14	42,713,000[a]	105.2	35,802,000	+19.3[b]
Okanagan	Okanagan	Okanagan	Penticton	5	214,900	72.8	277,860	-22.7

[a]Should have read 39,363,000. [b]Should have read 9.9.

Very much the same conditions obtained in the Coastal Belt, there being a gradual runoff with the exception of April in all areas adjacent to Vancouver. Summer temperature on the Coast was slightly below the average and considerably lower than that of 1942.

Table 1 gives the summer precipitation and temperature in per cent of normal. Table 2 shows the forecast runoff in acre-feet with percentage of error from the actual.

Coastal Area--The water-content of the snow was 90 per cent of an eight-year average. The April precipitation being 40 per cent above normal caused an immediate heavy runoff from the snow-cover on the lower mainland, so that by the end of the month, reservoirs were mostly full and, as predicted, capacity well sustained during the summer.

The Stave River during April to July had nearly a normal discharge, it being only 2.3 per cent above a 34-year average. The discharge was 16 per cent above that for the same months of 1942. For the same period the discharge from Powell Lake was eight per cent above normal and 18 per cent above that of 1942.

Okanagan Basin--The runoff from April to July for this Basin was forecast to be 73 per cent of normal. This is 23 per cent below the actual. During these months there was normal precipitation over the area, with temperatures three per cent below the average.

Evaporation-records at Summerland show that 10.23 inches was the total evaporation from the pan during June and July. This was 8.6 per cent below the average for 16 years. Assuming that the losses from Okanagan Lake were, say, 80 per cent of the above, it would give an added inflow to the lake (runoff-measurements are made at the lake-outlet) of approximately 57,000 acre-feet.

East Kootenay--The forecast for the April to August runoff for the Elk and Kootenay (at Wardner) rivers was for 126 per cent of average. The forecast was too high by 35 per cent. The actual runoff was less than that of 1942 by 25 per cent.

North Kootenay Area--The inflow for the period April to August at the north end of Kootenay Lake from the Lardeau and Duncan rivers was predicted to be 118 per cent of a nine-year average flow. This prediction was 30 per cent more than the actual of 2,090,000 acre-feet. The actual was one per cent more than that of 1942.

West Kootenay and Arrow Lake Area--The forecast for April to August for the Kootenay River at Glade was for 122 per cent of average, giving 18,730,000 acre-feet; this was 4.8 per cent of the actual. The actual was more than that of 1942 by 9.1 per cent.

Columbia Basin--The forecast for the discharge of the Columbia River at Golden for April to August was for 116 per cent of average, which proved to be 26 per cent above the actual runoff, the latter being approximately 95 per cent of that for 1942. At Revelstoke, the runoff of the Columbia for the same period was 122 per cent of average, but less than that of 1942 by five per cent. The forecast which was for 104 per cent of average was too high, differing by 22 per cent from the actual. In the forecast for the Columbia River at Trail, the normal used was in error, the correct normal being 37,417,000 acre-feet; consequently, the prediction of 105 per cent of this would give 39,363,000 acre-feet (not 42,713,000) which is 9.9 per cent above the actual, instead of 19 per cent as shown in Table 2. The above is for the period April to August. The actual runoff for these months was 1.6 per cent greater than that in 1942.

Department of Lands, Water Rights Branch,
Victoria, B. C.

DISCUSSION

H. P. BOARDMAN (Forecast Committee, Nevada Cooperative Snow-Surveys, Reno, Nevada)--Only two coastal basins, the Powell and the Fraser, are listed in this report and no forecast is mentioned for either of them. The other basins listed are all tributary to the Columbia and all but one of them join the main stream above the gaging-station at Trail which is near the International Boundary. The Okanagan is the tributary which joins the Columbia in the State of Washington.

The forecast of discharge of the Columbia at Trail, corrected in a foot-note of Table 2, was 39,363,000 acre-feet while the actual was 35,802,000 or 9.9 per cent of actual below the forecast. Of the nine tributaries listed, all but one, the Okanagan, fell short of the forecasts by from 4.2 to 49.2 per cent of the actual runoffs--only three of them being closer than 20 per cent. The Okanagan exceeded the forecast by 22.7 per cent of the actual runoff.

According to Mr. Frame's discussion, spring and summer precipitation and temperatures were not enough divergent from normal to help much in explaining the great discrepancies between forecasts and actual runoff, so apparently there is room for much improvement in forecasting these rivers.

COMPARISON OF THE 1943 AND 1942 WATER-SUPPLY FORECAST WITH THE MEASURED RUNOFF FOR COLUMBIA RIVER BASIN

J. C. Marr and Wayne D. Criddle

The winter of 1942-43 was characterized by the greatest mountain snow-cover since snow-surveys in Columbia River Basin were initiated. Likewise the snow-water depth as indicated by snow-surveys was larger than ever before. Considerable extension of forecast curves was required to determine the probable runoff.

The spring, summer, and fall of 1943 were dry throughout the Basin. It has been interesting to note that the heavier than usual runoff from mountain snow-cover had the effect of keeping stream-flow above normal until December, notwithstanding the dry season.

The actual runoff of 1943 has been determined for relatively few watersheds at this time, and in some cases these figures are tentative. They compare as in Table 1 with the forecasts based on the snow-surveys of April 1, 1943.

Analyses of the water-supply forecasts for the season of 1942 were not presented at the usual time during the following winter due to disruptions caused by the war.

The mountain snow-cover during the winter of 1941-42 was light and the water-supply forecasts which were made in April, 1942, were correspondingly low. Very heavy, local rainfall in the northern parts of the Basin during the months of May, June, and July greatly augmented the runoff from the snow-cover and accounted for wide differences between the forecast and the measured runoff. On the other hand, the precipitation was close to normal throughout Snake River Basin and relatively satisfactory agreement between forecast and measured runoff resulted (see Table 2).

The complete tabulation of comparisons cannot be given at this time because the runoff data for 1942 are not published and all of the unpublished figures are not at hand.

Table 1--Comparison of forecast and actual runoff, 1943

Stream	Runoff for period April 1 to September 30, 1943		
	Forecast	Measured	Deviation
	ac-ft	ac-ft	pct
Columbia River at Birchbank, B. C.	41,000,000	38,518,000	+ 6.4
Spokane River at Post Falls, Idaho	3,900,000	3,757,290	+ 3.8
Clearwater River at Spalding, Idaho	9,000,000	11,276,900	-20.2[a]
Salmon River at Whitebird, Idaho	9,000,000	9,661,000	- 6.8
Snake River near Moran, Wyoming	1,300,000	1,223,470	+ 6.3
Snake River near Heise, Idaho	5,400,000	5,442,320	- 0.8
Snake River at Weiser, Idaho	10,000,000	11,457,500	-12.7
Columbia River near The Dalles, Oregon	105,000,000	112,591,000	- 6.7
Boise River at Dowling Ranch, Idaho, and Moore Creek near Arrowrock, Idaho	2,700,000	2,840,000	- 4.9

[a] Forecast curve incorrectly drawn because of insufficient records of high runoff, the record for 1944 should obviate future misinterpretations.

Table 2--Comparison of forecast and actual runoff, 1942

Stream	Runoff for period April 1 to September 30, 1942		
	Forecast	Measured	Deviation
	ac-ft	ac-ft	pct
Kootenai River at Leonia, Idaho	4,500,000	8,780,800	-48.8
Clark Fork River near Heron, Montana	6,000,000	9,584,000	-37.4
Spokane River at Post Falls, Idaho	1,700,000	1,829,250	- 7.1
Clearwater River at Spalding, Idaho	5,100,000	6,073,100	-16.0
Salmon River at Whitebird, Idaho	4,000,000	6,543,600	-38.9
Snake River at Weiser, Idaho	5,200,000	6,915,800	-24.8[a]
Snake River near Moran, Wyoming	650,000	701,370	-7.3
Snake River near Heise, Idaho	2,450,000	3,238,860	-24.4[a]
Big Wood River and Big Wood Slough at Hailey, Idaho	200,000	290,210	-31.1
Boise River at Dowling Ranch and Moore Creek near Arrowrock, Idaho	1,000,000	1,227,400	-22.7

[a] The discharges of Snake River near Heise, Idaho, and at Weiser, Idaho, are affected by the consumptive use of water on large areas of irrigated land, consequently large deviation of the forecast runoff from that measured may be unavoidable at times.

U. S. Soil Conservation Service,
Boise, Idaho

ACCURACY OF FORECASTS OF RUNOFF IN UTAH, 1942 AND 1943

George D. Clyde

In Utah, in 1942, 14 out of 17 forecasts were within ten per cent of the actual and, in 1943, 12 out of 13 forecasts were within ten per cent.

Four streams for 1943 have not been reported.

Utah State Agricultural College,
Logan, Utah

SUMMARY OF FORECASTS OF RUNOFF TRIBUTARY TO STORAGE-RESERVOIRS ON UPPER SAN JOAQUIN RIVER

W. A. Lang

The Southern California Edison Company's Big Creek hydroelectric development is served by three storage-reservoirs, namely, Florence, Huntington, and Shaver Lakes, having a combined capacity of 288,523 acre-feet. These three reservoirs impound the runoff of Bear Creek, Mono Creek, South Fork San Joaquin River, Big Creek, Pitman Creek, and Stevenson Creek. The combined area of the six drainage-basins is 450 square miles, 45 per cent of which is above an elevation of 10,000 feet.

Forecast for 1942--Using the direct method of forecasting we predicted on April 1, 1942, a runoff of 627,000 acre-feet. The actual runoff received between November 1 and July 31 was 683,400 acre-feet, indicating an error of -8.3 per cent for the forecast for 1942. An analysis of the runoff received from each of the six watersheds involved shows that the Big Creek, Pitman Creek, and Stevenson Creek drainages produced about 29,400 acre-feet more than forecast, indicating that there was above-normal snow-pack at the lower elevations for the season of 1942. (See Table 1.)

Forecast for 1943--Using the direct method of forecasting we predicted on April 1, 1943, a runoff of 660,000 acre-feet. The actual runoff received between November 1 and July 31 was 624,400 acre-feet, indicating an error of +5.7 per cent for the forecast for 1943. An analysis of the runoff received from each of the six watersheds involved shows that the Bear Creek and South Fork San Joaquin River drainages produced 44,500 acre-feet less than forecast, indicating that there was a below-normal snow-pack at the higher elevations for the season of 1943. This conclusion was confirmed by the snow-surveys made on other snow-courses at high elevations and received after our forecast was made. (See Table 1.)

General--In order to obtain a better idea of the distribution of the snow-pack in our area in the future, we have during the summer of 1943 established five new snow-courses and constructed two new snow-surveyor cabins. The new courses are Nellie Lake (elevation 8,250 feet), Blaney Meadow (elevation 7,700 feet), Heart Lake (elevation 10,100 feet), Colby Meadow (elevation 10,000 feet), and Emerald Lake (elevation 10,500 feet). One new cabin is located near Blaney Meadows and one is located in McClure Meadow (Evolution Valley). These cabins are stocked and will permit surveys of the new courses in the South Fork San Joaquin River Area beginning with the surveys of

Table 1--Summary of forecast and actual runoff, 1942 and 1943

Drainage-basin	November, 1941, to July, 1942			November, 1942, to July, 1943		
	Forecast	Actual	Error	Forecast	Actual	Error
	ac-ft	ac-ft	pct	ac-ft	ac-ft	pct
South Fork, San Joaquin River	247,000	255,900	- 3.5	260,000	222,400	+16.9
Big Creek	122,000	140,800	-13.4	129,000	131,200	- 1.7
Mono Creek	114,000	125,900	- 9.5	120,000	123,100	- 2.5
Bear Creek	69,000	75,200	- 8.2	72,000	65,100	+10.6
Pitman Creek Stevenson Creek	75,000	85,600	-12.4	79,000	82,600	- 4.4
Combined	627,000	683,400	- 8.3	660,000	624,400	+ 5.7

April, 1944. Plans have also been made for erecting three more cabins and selecting additional courses during the summer of 1944 in order to better cover the Mono-Bear Area and the Pitman-Stevenson Area.

It is believed that improved forecasts will be possible when data from the newly established and proposed new snow-courses become available and have been correlated with data collected at existing stations since 1930. For power-generation purposes it is desirable to have an idea of the probable runoff as early in the season as possible. We, therefore, usually begin our forecasts on February 1 using snow-survey data from the key courses at Huntington Lake and Kaiser Pass. The prediction in February is followed by monthly, or in some cases semi-monthly, forecasts during March and April, in each case taking advantage of current snow-surveys and an estimate of the precipitation-expectancy for the remainder of the season to April 1.

Southern California Edison Company,
Los Angeles, California

SNOW-RUNOFF FORECAST, MOKELUMNE WATERSHED

L. Standish Hall

Precipitation from the seven stations used as indices of the mean on the Mokelumne Watershed above Pardee Reservoir for the fiscal year July 1, 1941, to June 30, 1942, averaged 53.95 inches, or 123 per cent of normal. The seasonal precipitation last year was 49.53 inches, or 112 per cent of normal. The precipitation was deficient during the early part of the season, but was well above normal during the month of December. In January and February the precipitation was approximately normal, but fell off very markedly during March. However, in April and May the precipitation was considerably above normal. No precipitation occurred in June.

Observations in the high mountains showed that snow first accumulated on the ground on November 17. However, this fall was very light and melted within a short period of time. The first permanent snow-accumulation started on December 15. Although precipitation was quite heavy in December, the temperatures in the high mountains were above average and the total depth of snow on the ground was rather light at the end of the month. The heaviest accumulation of winter snow occurred during a storm lasting from January 22 to February 7, during which period some snow fell nearly every day. During the remainder of February and the month of March the depth of snow did not increase, but the scanty precipitation resulted in a packing of the snow already on the ground.

The outbreak of war on December 7 caused a curtailment of weather information under orders of the War Department so that a continuous record of the snow on the ground is not available. Reports of the California Cooperative Snow-Survey on April 1 indicated that the precipitation at this date on the Mokelumne Watershed was 106 per cent of normal, while the snow-pack was only 96 per cent of normal. Considering the entire Sierra range, the precipitation exceeded the normal to the greatest extent at the north end of the Sacramento Valley, gradually dropping off to the south until amounts below normal were recorded near Mount Whitney at the south end of the San Joaquin Valley. Due to warm rains and melting of the snow-pack during the early part of the winter months, the snow on the ground on April 1 was below normal for streams draining into the Sacramento Valley, but on the high mountain ranges of the Southern Sierras the snow-pack was above normal.

During the current year no precipitation occurred during the snow-survey period between March 27 and April 3. However, shortly after the survey had been completed, heavy precipitation occurred during April and May with the result of the average for the Mokelumne Watershed for these two months was 13.67 inches, or 7.67 inches above the normal. An upward revision of the first snow-runoff estimate, based on the data of April 1, was therefore necessary.

As in the past two years, there was but little snow on the ground below the 6,000-foot elevation on April 1, and it was also found that the runoff did not follow the relation determined from the snow-survey of April 1 for the years 1935-39. A relocation of some of the snow-courses was made at the end of the season of 1939 and it is possible that the amount of snow measured at the relocated courses have altered the location between depth of snow on the ground on April 1 and the runoff at the gaging-station near Mokelumne Hill. The total runoff for the current year, however, appeared to agree with the results obtained in the past two years and a new relation was determined, based on the past three seasons, shown on Figure 1. A segregation has been made in the water-content

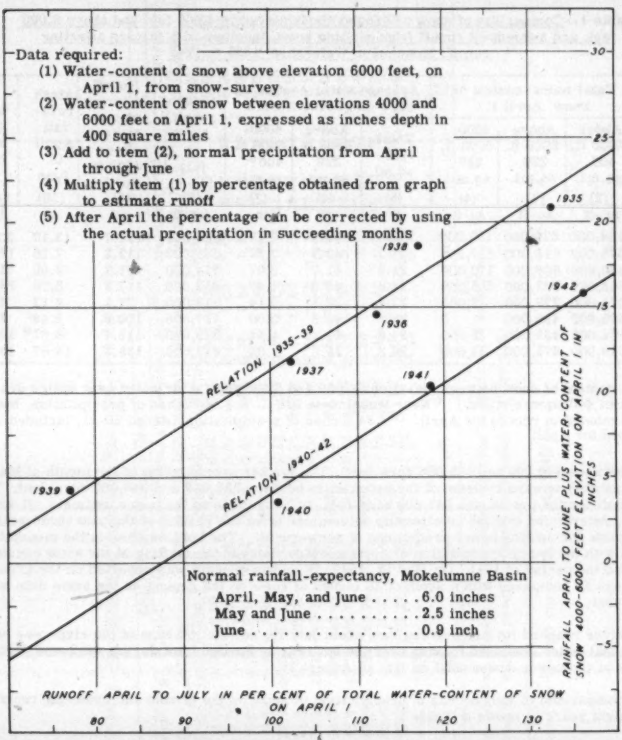
Data required:
(1) Water-content of snow above elevation 6000 feet, on April 1, from snow-survey
(2) Water-content of snow between elevations 4000 and 6000 feet on April 1, expressed as inches depth in 400 square miles
(3) Add to item (2), normal precipitation from April through June
(4) Multiply item (1) by percentage obtained from graph to estimate runoff
(5) After April the percentage can be corrected by using the actual precipitation in succeeding months
RELATION 1935-39
RELATION 1940-42
1935
1936
1937
1938
1939
1940
1941
1942
Normal rainfall-expectancy, Mokelumne Basin
April, May, and June . . . . . 6.0 inches
May and June . . . . . 2.5 inches
June . . . . . 0.9 inch
RAINFALL APRIL TO JUNE PLUS WATER-CONTENT OF SNOW 4000-6000 FEET ELEVATION ON APRIL 1 IN INCHES
30
25
20
15
10
5
0
-5
RUNOFF APRIL TO JULY IN PER CENT OF TOTAL WATER-CONTENT OF SNOW ON APRIL 1
80
90
100
110
120
130

Fig. 1--Runoff from melting snow above 6000-foot elevation, April through July, at Mokelumne Gaging-Station, Mokelumne River Basin

of the snow below and above 6000-foot elevation. The former has been included in the precipitation as explained on Figure 1.

Fred H. Paget, Engineer in charge of the California Cooperative Snow-Survey, made an estimate of the runoff based solely on the results of the water-content of the snow at six of the stations above 6000-foot elevation. His original estimate indicated a probable runoff of 500,000 acre-feet during the snow-melt period which was increased on May 1 to 550,000 acre-feet. No further snow-surveys were made by the State and therefore the estimate of runoff was not again revised for the heavy precipitation for the month of May. The estimate of runoff from melting snow was prepared by the Hydrographic Division by the method used in previous years. The total water-content on April 1 was 519,400 acre-feet, or slightly less than that computed for the previous year. At the beginning of the season it was not definitely determined whether the runoff would follow the relation of 1935-39 or the relation established from the previous two years of 1940-41. As a result, two estimates of runoff were made, based on both relationships. On April 1 it was estimated that the total runoff from melting snow between April 1 and July 31 would range between 425,000 and 530,000 acre-feet. On May 1 this estimate was increased as a result of the precipitation in

Table 1--Comparison of snow on ground above elevation 4,000 feet and above 6,000 feet, and subsequent runoff from melting snow, together with factors affecting runoff, Mokelumne Watershed, 1935 to 1942

Year	Total water-content of snow, April 1			Average water content of snow on ground April 1			Natural runoff[b] April to July	Runoff, in terms water-content above 6000 ft, April 1	Mean rain-fall April to June	Sum (7) and (10)
	Above 4000 ft, 400 sq.mi.	Above 6000 ft, 229 sq.mi.	4000-6000 ft, 229 sq.mi.	Total 400 sq.mi.	Above 6000 ft, 229 sq.mi.	4000-6000 ft, 400[a] sq.mi.				
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
	ac-ft	ac-ft	ac-ft	in	in	in	ac-ft	pct	in	in
1935	584,000	419,000	165,000	27.4	34.3	7.65	556,000	132.7	13.17	20.82
1936	675,000	518,000	157,000	31.7	42.5	7.37	581,000	112.2	7.10	14.47
1937	680,000	508,000	172,000	31.9	41.7	8.07	514,000	101.2	3.66	11.73
1938	948,000	693,000	255,000	44.5	56.8	11.97	812,000	117.2	6.55	18.52
1939	278,000	275,000	3,000	13.1	22.5	0.14	212,000	77.1	4.12	4.26
1940	495,000	495,000	0	23.2	40.6	0.00	497,000	100.4	3.48[c]	3.48
1941	524,000	489,000	35,000	24.6	40.1	1.64	579,000	118.4	8.67[d]	10.31
1942	519,000	475,000	44,000	24.3	38.9	2.06	647,600	136.3	13.67	15.73

[a] Water-content of snow between elevations 4,000 and 6,000 feet, distributed over entire drainage-area of 400 square miles. [b] Near Mokelumne Hill. [c] 1.60 inches of precipitation, March 31, included in record for April. [d] 1.34 inches of precipitation, March 29-31, included in record for April.

April to between 470,000 and 575,000 acre-feet. The further precipitation of the month of May resulted in another upward revision of the estimate to between 535,000 and 640,000 acre-feet. The actual runoff for the period was 647,600 acre-feet, or very close to the upper estimate. It was, therefore, determined that the relationship determined from the results of the past three years is the best guide for making future predictions of snow-runoff. The cold weather in the mountains, combined with the heavy precipitation of April and May, delayed the melting of the snow considerably beyond the period of 1941. On May 15, 1942, 70 inches of snow was reported on the ground at Soda Springs as compared with a depth of 28 inches of snow on the ground on the same date of the previous year.

The river reached its summer regimen about July 15, but the low flow of the river was so well sustained that water continued to pass over the spillway at Pardee Dam during week-end partial shutdowns of the power-house until as late as August 17.

The comparison of the records of precipitation of snow on the ground and resulting runoff for the past eight years is shown in Table 1.

Forecast of snow-runoff for Mokelumne Watershed--Precipitation at the seven stations used as indices of the mean on the Mokelumne Watershed above Pardee Reservoir, together with that of Camp Pardee, is assembled in Table 2 for the fiscal year July 1, 1942, to June 30, 1943. The precipitation on the watershed above Pardee Reservoir during the past season averaged 54.24 inches or 125 per cent of normal. The seasonal precipitation for the prior year was 53.95 inches or 123 per cent of normal. Heavy precipitation occurred early in the season in November and the months of January and March also were well above normal.

Snow first accumulated on the ground in the high Sierras on November 3. The fall was rather light until November 17, when a heavy storm increased the snow-accumulation. Subsequent storms added to the snow-pack, which reached a maximum of 112 inches on the ground at Soda Springs on February 9. The relatively mild winter caused an early melting of the snow. No snow remained on the ground at Soda Springs on May 5.

The report of the California Cooperative Snow-Survey on April 1 indicated that the precipitation on the Mokelumne Watershed was 125 per cent of normal, while the snow-pack was 104 per cent of normal. Considering the entire Sierra Range, the precipitation was 160 per cent of normal at the southern end of the San Joaquin Valley, gradually decreasing to 110 per cent toward the north end of the Sacramento Valley. The warm rains of the winter months caused an unusually large

Table 2--Precipitation on Mokelumne Watershed, 1942-1943

Month	Station and elevation in feet																		
	Electra[c], 699 feet		Tiger Creek[c], 2341 feet		West Point[c], 2326 feet		Big Trees[d], 4700 feet		Twin Lakes[c], 7920 feet		Blue Lakes[c], 8000 feet		Salt Spgs.[d], 3700 feet		Mean Watershed Precip.[b]		Pct[e] nor.	Camp Pardee 670 feet		Pct[e] nor.
	Inch	Cum.	Inch	Cum.	Inch	Cum.	Inch	Cum.	Inch	Cum.	Inch	Cum.	Inch	Cum.	Inch	Cum.		Inch[c]	Cum.[c]	
July	Tr.	0.00	0.00	0.00	Tr.	0.00	0.00	0.00	Tr.	0.00	0.02	0.02	0.00	0.00	0.00	0.00	...	0.00	0.00	...
Aug.	0.00	0.00	0.00	0.00	Tr.	0.00	0.00	0.00	0.38	0.38	0.07	0.09	0.06	0.06	0.07	0.07	23	0.00	0.00	...
Sep.	0.00	0.00	0.00	0.00	Tr.	0.00	0.10	0.10	0.14	0.52	0.47	0.56	0.76	0.82	0.21	0.28	27	0.03	0.03	21
Oct.	0.16	0.16	0.48	0.48	0.40	0.40	0.90	1.00	0.53	1.05	0.79	1.35	0.53	1.35	0.54	0.82	25	0.07	0.10	9
Nov.	10.69	10.85	14.44	14.92	11.70	12.10	10.10	11.10	10.41	11.46	8.24	9.59	10.67	12.02	10.89	11.71	180	5.21	5.31	170
Dec.	4.22	15.07	7.59	22.51	5.30	17.40	9.65	20.75	6.87	18.33	6.23	15.82	6.61	18.63	6.64	18.35	138	2.63	7.94	124
Jan.	8.27	23.34	14.24	36.75	12.13	29.53	23.10	43.85	13.80	32.13	14.04	29.86	15.00	33.63	14.37	32.72	150	6.12	14.06	133
Feb.	4.48	27.82	5.62	42.37	4.77	34.30	8.57	52.42	5.70	37.83	6.05	35.91	6.56	40.19	5.96	38.68	126	3.05	17.11	111
Mar.	9.03	36.85	13.60	55.97	11.17	45.47	13.55	65.97	9.24	47.07	9.68	45.59	10.08	50.27	10.91	49.59	132	6.85	23.96	127
Apr.	2.69	39.54	3.24	59.21	2.88	48.35	3.94	69.91	1.91	48.98	2.45	48.04	2.56	52.83	2.81	52.40	128	2.41	26.37	128
May	0.09	39.63	0.43	59.64	0.30	48.65	1.50	71.41	1.14	50.12	1.72	49.76	0.84	53.67	0.86	53.26	125	0.06	26.43	124
June	0.50	40.13	1.20	60.84	0.86	49.51	0.00	71.41	1.60	51.72	1.81	51.57	0.91	54.58	0.98	54.24	125	0.17	26.60	123
Total	40.13	....	60.84	....	49.51	....	71.41	....	51.72	....	51.57	....	54.58	....	54.24	....	...	26.60	....	...
Pct of normal	128	....	132	....	125	....	142	....	114	....	108		125	....	125	....	...	123	....	...

[b] Average of seven stations closely approximates the mean rainfall on the watershed.

[c] United States Weather Bureau records, Blue Lakes listed as Tamarack.

[d] California Cooperative Snow-Survey records.

[e] Normals computed for 70-year period, 1870-71 to 1940-41.

Table 3--California Cooperative Snow-Survey, Mokelumne River, 1943

Snow-Course	Elevation	Date Survey	Depth snow	Water-content	Pct normal
	ft		in	in	
Carson Pass	8600	Mar. 28	112.7	48.6	116
Blue Lakes	8000	Mar. 31	113.0	45.1	110
Twin Lakes	7900	Mar. 28	84.3	36.5	. . .
Tragedy Springs	7900	Mar. 31	124.8	52.7	. . .
Wheeler Lake	7800	Mar. 28	144.0	65.2	. . .
Pacific Valley	7500	Mar. 27	106.5	47.7	108
Lake Alpine	7500	Mar. 29	106.4	47.8	107
Silver Lake	7300	Mar. 27	55.5	23.5	90
Corral Flat	7300	Mar. 31	102.2	46.6	. . .
Bear Valley Ridge	6700	Mar. 30	56.9	24.3	79
Lumberyard Station	6600	Mar. 30	68.6	29.8	. . .
Big Meadow	6500	Mar. 31	67.5	31.7	. . .
Cottage Springs	5700	Apr. 1	16.0	7.8	. . .
Hams Station	5600	Mar. 28	0.0	0.0	. . .
Dorrington	4800	Apr. 1	0.0	0.0	. . .
Antelope Springs	4350	Apr. 1	0.0	0.0	. . .

Table 4--Estimate of total water-content of snow, April 1, 1943, Mokelumne Watershed

Contour-interval	Drainage-area	Water-content snow	Total water-content snow
ft ft	sq.mi.	in	ac-ft
4,000- 5,000	88	0	0
5,000- 6,000	83	3.9	17,000
6,000- 7,000	63	28.6	96,000
7,000- 8,000	91	45.7	222,000
8,000-10,000	75	46.8	187,000
Total or mean	400	24.5	522,000

runoff between November and March. On April 1 the natural runoff was 137 per cent of normal. As a result, the snow-melt between April 1 and July 31 was only slightly above normal, but because of the large volume of early runoff the total discharge for the season was well in excess of normal. The results of the snow-survey by the California Cooperative Snow-Survey, as of April 1, for the Mokelumne Watershed, are given in Table 3.

During the current year, very little precipitation occurred during the snow-survey period between March 27 and April 1. The precipitation during the months of April, May, and June was below normal, and hence the total runoff for the season April 1 to July 31 was below the estimate of April 1. For the past three successive years, there has been but little snow on the ground below the 6000-foot elevation on April 1. Since 1940, the relation between runoff and snow on the ground has been greater than for previous years. For the fourth successive year, the relation has followed that for 1940-42.

Fred H. Paget, Engineer in charge of the California Cooperative Snow-Survey, made an estimate of the runoff for the Mokelumne River on April 1, predicting a flow of 570,000 acre-feet at the station near Mokelumne Hill. The actual runoff for the period was 525,400 acre-feet.

Table 5--Comparison of snow on ground above elevation 4,000 feet and above 6,000 feet, and subsequent runoff from melting snow, together with factors affecting runoff, Mokelumne Watershed, 1935 to 1943

Year	Total water-content of snow, April 1			Average water-content of snow on ground April 1			Natural runoff[b] April to July	Runoff, in terms water-content above 6000 ft, April 1	Mean rain-fall April to June	Sum (7) and (10)
	Above 4000 ft, 400 sq.mi.	Above 6000 ft, 229 sq.mi.	4000-6000 ft, 171 sq.mi.	Total 400 sq.mi.	Above 6000 ft, 229 sq.mi.	4000-6000 ft, 400[a] sq.mi.				
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
	ac-ft	ac-ft	ac-ft	in	in	in	ac-ft	pct	in	in
1935	584,000	419,000	165,000	27.4	34.3	7.65	556,000	132.7	13.17	20.82
1936	675,000	518,000	157,000	31.7	42.5	7.37	581,000	112.2	7.10	14.47
1937	680,000	508,000	172,000	31.9	41.7	8.07	514,000	101.2	3.66	11.73
1938	948,000	693,000	255,000	44.5	56.8	11.97	812,000	117.2	6.55	18.52
1939	278,000	275,000	3,000	13.1	22.5	0.14	212,000	77.1	4.12	4.26
1940	495,000	495,000	0	23.2	40.6	0.00	497,000	100.4	3.48[c]	3.48
1941	524,000	489,000	35,000	24.6	40.1	1.64	579,000	118.4	8.67[d]	10.31
1942	519,000	475,000	44,000	24.3	38.9	2.06	647,600	136.3	13.67	15.73
1943	522,000	505,000	17,000	24.5	41.4	0.80	525,400	104.0	4.65	5.45

[a] Water-content of snow between elevations 4,000 and 6,000 feet, distributed over entire drainage-area of 400 square miles. [b] Near Mokelumne Hill. [c] 1.60 inches of precipitation, March 31, included in record for April. [d] 1.34 inches of precipitation, March 29-31, included in record for April.

The estimate of runoff from melting snow was prepared by the Hydrographic Division by the method used in previous years. The total water-content of the snow on the ground above the 4000-foot elevation divided into various zones of equal elevations is given in Table 4.

The total water-content of snow on the ground was 522,000 acre-feet, or slightly more than that computed for the previous year. Using the relation between runoff and snow on the ground for the years 1940-42, it was estimated on April 1 that the total runoff would be 550,000 acre-feet. Due to deficient precipitation following April 1, this estimate was progressively decreased to 535,000 acre-feet on May 1 and 525,000 acre-feet on June 1.

The river reached the summer regimen about July 1 and the last flow over the spillway at Pardee Dam occurred on July 6. The comparison of the records of precipitation, of snow on the ground, and the resulting runoff for the past nine years is shown on Table 5.

East Bay Municipal Utility District,
Oakland, California

SIERRA STREAMS IN CALIFORNIA, 1942 AND 1943

Fred Paget

Table 1--Summary of forecasts and actual results

Drainage-area or stream gaging-station	April to July, 1942 [a]			April to July, 1943		
	Forecast	Actual [b]	Diff.	Forecast	Actual [b]	Diff.
	ac-ft	ac-ft	pct	ac-ft	ac-ft	pct
South Fork, Pit River near Likely	37,000	49,050	-25	45,000	52,620	-14
Pit River near Ydalpom	1,300,000	1,367,130	- 5	1,120,000	1,236,740	- 9
Sacramento River at Kennett	2,100,000	2,455,600	-14	1,950,000	1,996,000	- 2
Feather River near Oroville	2,450,000	2,870,200	-15	2,100,000	1,911,550	+10
Bowman Area, Middle Yuba and Canyon Creek	130,000	144,730	-10	125,000	122,120	+ 2
South Fork, Yuba River at Lang's Crossing	275,000	296,975	- 7	250,000	244,088	+ 2
Yuba River at Smartsville	1,250,000	1,623,600	-23	1,300,000	1,104,670	-15
Middle Fork, American River near Auburn	620,000	806,500	-23	650,000	530,500	+23
American River at Fair Oaks	1,450,000	2,054,800	-29	1,500,000	1,387,800	+ 8
North Fork, Mokelumne River near West Point	500,000	592,650	-16	525,000	481,600	+ 8
Mokelumne River near Mokelumne Hill	550,000	666,000	-17	570,000	530,120	+ 8
Middle Fork, Stanislaus River near Avery	400,000	492,000	-19	400,000	413,740	- 3
Stanislaus River below Melones P. H.	870,000	1,038,200	-16	880,000	847,430	+ 4
Tuolumne River near Hetch Hetchy	740,000	818,200	-10	700,000	744,180	- 6
Tuolumne River at La Grange	1,550,000	1,671,000	- 7	1,350,000	1,371,500	- 2
Merced River at Pohono Bridge	450,000	491,730	- 8	430,000	425,200	+ 1
Merced River at Exchequer	820,000	903,600	- 9	725,000	718,200	+ 1
Big Creek at Huntington Lake	115,000	126,270	- 9	100,000	114,800	-15
South Fork, San Joaquin River at Florence Lake	250,000	229,090	+ 9	200,000	201,300	- 1
San Joaquin River above Big Creek	1,280,000	1,385,600	- 8	1,150,000	1,137,140	- 1
San Joaquin River at Friant	1,540,000	1,680,400	- 8	1,300,000	1,352,250	- 4
North Fork, Kings River below Rancheria Creek	345,000	342,650	+ 1	290,000	290,140	- 0
Kings River above Piedra	1,600,000	1,553,200	+ 3	1,300,000	1,380,700	- 6
Kaweah River near Three Rivers	350,000	361,780	- 3	320,000	387,860	-17
Kern River near Bakersfield	440,000	538,200	-18	600,000	684,270	-12

[a] Rains in May increased the runoff above the forecasts; these rains were heaviest in the northern Sierra; after May 1 no revised forecasts were published.

[b] The stream flows as forecast and as recorded above are the full natural flows from the watershed; stream-flows as measured have been corrected for modification due to reservoir storage or diversion from or to the watersheds.

State Division of Water Resources,
Sacramento, California

RESULTS OF FORECAST OF 1943 OF FLOW INTO LAKE MEAD

J. R. Riter

The Bureau of Reclamation attempts to forecast, early in the successive months of February, March, April, and May, the subsequent inflow through July. These forecasts are based in large measure upon snow-measurements made on the first of these successive months, but we have found from experience that the results thus gained are certainly not infallible. We have therefore tempered our interpretations of snow-survey data by making a parallel forecast based upon cumulative precipitation subsequent to September 30 of the previous year, and, finally, by exercise of our best judgment.

From correlations between past observed snow-pack and subsequent flood-season runoff, we attempt to forecast minimum probable, mean probable, and maximum probable flood-season inflow to Lake Mead. The results of our forecasts for 1943 based solely upon snow-measurements are summarized in Table 1.

Table 1--Forecasts for 1943 based upon snow-measurements

Date forecast	Runoff period covered	Runoff			
		Estimated			Actual
		Min. prob.	Mean prob.	Max. prob.	
1943	1943	ac-ft	ac-ft	ac-ft	ac-ft
Feb. 1	Feb.-July	6,700,000	10,500,000	14,400,000	8,640,000
Mar. 1	Mar.-July	5,900,000	9,600,000	13,700,000	8,290,000
Apr. 1	Apr.-July	7,500,000	9,800,000	13,000,000	7,710,000
May 1	May-July	3,100,000	3,850,000	5,100,000	8,300,000

Our parallel forecasts based upon cumulative precipitation subsequent to September 30, 1942, gave the results in Table 2.

Table 2--Parallel forecasts for 1943 based on cumulative precipitation subsequent to September 30, 1942

Date forecast	Runoff period covered	Runoff			
		Estimated			Actual
		Min. prob.	Mean prob.	Max. prob.	
1943	1943	ac-ft	ac-ft	ac-ft	ac-ft
Feb. 1	Feb.-July	6,700,000	10,200,000	13,700,000	8,640,000
Mar. 1	Mar.-July	5,900,000	9,500,000	12,900,000	8,290,000
Apr. 1	Apr.-July	5,900,000	9,100,000	12,200,000	7,710,000
May 1	May-July	5,000,000	6,500,000	8,600,000	8,300,000

Table 3--Total content of Lake Mead at end of each month and releases

Month	Content	Release
1942-1943	ac-ft	ac-ft
Dec.	26,290,000	
Jan.	25,530,000	1,110,000
Feb.	25,050,000	830,000
Mar.	24,700,000	980,000
Apr.	25,180,000	920,000
May	26,300,000	1,020,000
June	27,810,000	1,040,000
July	28,130,000	1,110,000
Aug.	27,850,000	1,040,000
Sep.	27,280,000	1,040,000
Oct.	26,460,000	1,180,000
Nov.	25,710,000	1,180,000
Dec.	24,900,000	1,270,000

It will be noted that conditions experienced in April required drastic revisions of both forecasts, with that based upon snow-pack measurements being much more sensitive to the change in conditions, and, incidentally, this extreme sensitivity resulted in a forecast for May 1 disappointing in its accuracy.

In April, precipitation over the watershed was only 47 per cent of the mean for 1937-42. At the same time, snow-cover losses during April, 1943, were 10.27 inches as against a mean for 1936-42 of 4.14 inches. We have reasoned that a substantial part of our snow-cover losses during April went into recharge of ground-water, and subsequently contributed to stream-flow. That circumstance we evaluate as one of the deficiencies of a forecast based solely upon measured snow-pack. We have not as yet solved

the problem of introducing that element into our forecasts, and will, of course, welcome any suggestions from others who have encountered the same problem.

The operation of Lake Mead during 1943 was not particularly delicate, inasmuch as at no time was there prospect of flood-runoff beyond that which could be handled in routine fashion. No water was released from Lake Mead solely for the purpose of evacuating flood-control capacity. Total content of Lake Mead as of the last of each month of 1943, and monthly releases, are given in Table 3.

Total capacity of Lake Mead to the top of the spillway-gates is 31,140,000 acre-feet.

U. S. Bureau of Reclamation, Branch of Project Planning,
Denver, Colorado

SNOW-TEMPERATURE STUDIES AND APPARATUS AT THE SODA SPRINGS, CALIFORNIA, COOPERATIVE SNOW-RESEARCH PROJECT

R. W. Gerdel

The need for information upon the transfer of heat into and through the snow-pack has been well presented by Wilson [see 1 of "References" at end of paper], Light [2], Bernard and Wilson [3], and Merriam [4, 5, 6, 7]. Such hypotheses as presented by Wilson and theoretical formula as developed by Light are applicable, in the final analysis, only as a result of more complete information on temperature-gradients within the snow-mantle. The development of calorimetric procedures for determining the thermal quality of the snow-pack will be much simplified by a knowledge of the temperature at different horizons within the snow. Where temperatures are consistently below freezing, density and depth may provide sufficient information since thermal quality, under such conditions, will be 100 per cent or better. Where snow-temperatures of 32° F are encountered thermal qualities of less than 100 per cent may be expected and samples at close vertical intervals within the pack may be necessary.

Selection of instruments for measuring snow-temperatures can be made from a wide field. Little is known about the adaptability of the many available instruments to the measurement of temperatures at various depths within the snow-mantle. Church [9] has used standard, full-immersion, mercurial thermometers sealed in thin-wall, large-bore glass tubes. Thermocouples were used with a sensitive reflecting galvanometer by Kerānen [8] as early as 1920. Church [9] installed thermohms or electrical-resistance thermometers in the snow at Soda Springs, California, in 1943. Recently a new liquid electrical-resistance thermometer has been developed by Dr. G. J. BOUYOUCOS at Michigan State College. With an alternating-current bridge of special design, this temperature-measuring device has a range from about 50,000 ohms at 100° F to 1,000,000 ohms at 32° F.

All temperature-measuring instruments are subject to certain limitations in their adaptability to snow-temperature measurements. The conditions under which they are used as well as the method of installation may influence the results obtained by any type of equipment that may be selected.

Limitations

Glass-stem mercurial thermometers--Ordinary mercurial thermometers may be divided into two classes, (a) those for total immersion and (b) those for partial immersion in the media to be tested. For snow-temperature measurements the total-immersion type is essential since the partial-immersion type may be in error by as much as a degree or more dependent upon the ambient temperature and the portion immersed. The limitations for the total-immersion type when used for snow-temperature measurement have been discussed by Wilson [10]. The mercury acts not only as a radiating black-body but also reflects some of the radiant energy, and these phenomena are not compensating. For depths in the snow sufficiently shallow to be affected by solar radiation such thermometers may give excessively high values. As we will show later, this phenomenon may extend to ten or more inches beneath the snow-surface. The use of a sealed-glass tube surrounding the thermometer produces a "greenhouse" effect which probably accounts for reported temperatures of as high as 35° F within the snow-pack.

Thermohms or electrical-resistance thermometers--Thermohms have a large mass with a relatively low specific heat. The three-strand, heavy, black, rubber-covered copper lead wires

also have a high capacity for absorption and conduction of heat. The installation of such equipment requires that attention be given to means of dissipating the heat absorbed by the lead wires. The use of an electrical current for measuring the resistance of the unit may, under some conditions, raise the temperature of that unit above that of the surrounding media. Such an error would result where the instrument was misused. Under proper conditions of use the current through the resistance unit is negligible when the bridge is in balance.

Thermocouples--Thermocouples of copper-constantan wire are extremely sensitive and readily adaptable to snow-temperature studies providing a sensitive potentiometer or reflecting galvanometer may be used. The current-output of thermocouples is so small that extremely sensitive apparatus is needed for measuring it. The size of the wire used in making up the thermocouple-junctions determines their sensitivity to temperature-changes. Small-diameter wire has the advantage of less mass and, therefore, junctions made of fine wire are less subject to temperature-conditions external to the media being studied. Since a reference-junction must be used, a problem is created in maintaining this junction at a uniform, constant temperature which is always known or which is fixed by some physical property, such as a mixture of ice and water with a constant temperature of 32°F. Potentiometers may have several types of compensating reference-junctions. The more sensitive types usually have a mercurial thermometer in contact with the reference-junction by which the temperature of this junction is determined. Under field-conditions, the errors in the mercurial thermometer may be superimposed upon the inherent limitations in thermocouples. Probably the most accurate method of measuring the small current-output of thermocouples is by use of a sensitive, low-resistance reflecting galvanometer in conjunction with a reference-junction maintained at constant, known temperature within a thermos flask.

Bouyoucos liquid electrical-resistance thermometer--The Bouyoucos thermometer consists of a very small glass bulb containing two electrodes and an organic electrolyte of high resistance. It is very sensitive at temperatures above 32°F but the sensitivity falls off rapidly at temperatures below freezing. Each thermometer must be independently calibrated for the length of lead wire used. Long leads, of more than ten or 12 feet, introduce a capacitance-effect of such magnitude that the specially designed bridge can only be brought into balance with difficulty. If the present defects and limitations in this instrument can be overcome the same alternating-current bridge can be used for both studies of soil- and snow-temperatures and of moisture, and possibly for determining the actual freezing-point of the soil-solution which may be at temperatures below the freezing isotherm.

Installation of temperature-measuring equipment at the Soda Springs Cooperative Snow-Research Project

Previous experience in studying soil- and air-temperature by thermocouples [11] had indicated the necessity of dissipating any heat absorbed by the lead wires before it could be conducted to the thermocouple-junction. At Soda Springs a wire-trellis was installed between two posts (Figs. 1, 2, 3). This trellis consisted of approximately eight-foot lengths of No. 9 galvanized iron wire which were spaced at one-foot intervals above the soil-surface to a height of 12 feet. An additional wire was installed at six inches above the soil-surface. Wire ends were wrapped about the wooden posts, one of which supported the elevated instrument-house, the other being a support for the snow-gage platform. Loose ends of the wire were left long to help dissipate heat and thus help to maintain the wires at the same temperature as the snow under which they would eventually be buried. Thermocouple and thermohm lead-wires were carried on these supporting wires and fastened by means of loosely wrapped No. 18 iron wire which also had long free ends. All lead wires were carried to one post and given several turns about the post at the same elevation as the temperature-element. Such an arrangement appears to effectually compensate for warmer or colder conditions of the ambient temperature above the snow-pack, but does not eliminate the effect of absorption of solar radiation by the temperature-element itself.

Thermohms are read with a direct-current Wheatstone bridge directly calibrated in °F and are read to an estimated 0°1F. Thermocouples are read by means of a two-ohm reflecting galvanometer to an actual 0°12 F. The reference-junction is always maintained at 32°F in a thermos flask of ice and water. The galvanometer-scale is sufficiently large to permit measurement of temperatures of 32° ± 15°F.

Results of studies with thermohms and thermocouples--Data obtained for the forepart of the season of 1943-44 indicate that for depths greater than ten inches beneath the snow-surface both thermohms and thermocouples are equally reliable as instruments for measuring snow-temperatures (Table 1).

Fig. 1--Elevated instrument house and platform for snow-gages, Soda Springs, California, December 14, 1943

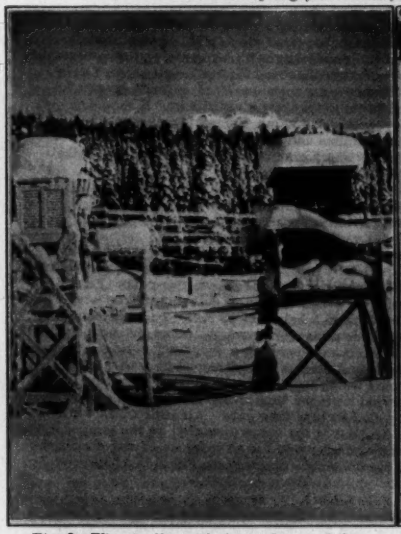

Fig. 2--Wire trellis with thermohms and thermocouples installed between instrument house and platform, Soda Springs, California, February 4, 1944

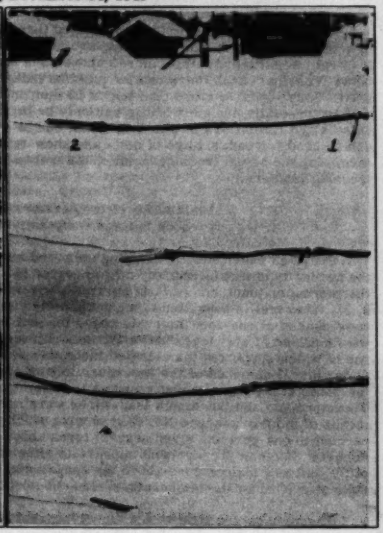

Fig. 3--Close-up of supporting wires carrying thermohms (1) and thermocouples (2), Soda Springs, California, February 1944

When atmospheric temperatures are rising or falling, thermohms in the upper ten inches of snow may fail to give the true snow-temperature. This is also true when solar radiation penetrates the snow to a sufficient depth to be absorbed by the thermohms. In such cases the large mass and low specific heat may cause them to lag behind the ambient temperature, or to give values considerably above 32°F within the snow-pack due to the absorption of solar radiation. The lag behind

Table 1--Temperature in the snow-pack and in the soil, SODA SPRINGS CALIFORNIA, 1943-1944
(Showing effect of ambient temperature and penetration of radiation on temperature-measuring elements)

Position of thermohm or thermocouple	January 30 at noon			February 10 at noon			February 13 at 10h		
	Depth in snow	Thermohm	Thermocouple	Depth in snow	Thermohm	Thermocouple	Depth in snow	Thermohm	Thermocouple
	in	°F	°F	in	°F	°F	in	°F	°F
1 foot below soil-surface	..	...	33.7	..	...	33.4	..	...	33.6
6 inch below soil-surface	..	33.5	33.0	..	33.1	32.8	..	33.3	32.8
On soil-surface	34	32.1	32.5	50	32.2	32.1	45	32.1	32.1
6 inch above soil-surface	28	32.0	32.0	44	32.0	32.0	39	32.0	32.0
1 foot above soil-surface	22	31.0	31.1	38	32.0	32.0	33	32.0	32.0
2 feet above soil-surface	10	28.9	30.2	26	32.0	32.0	21	32.0	32.0
3 feet above soil-surface	..	...	...	14	32.0	32.0	9	29.0	31.2
4 feet above soil-surface	..	...	...	2	37.6	32.0	..	...	...
Air-temperature, °F		34.0			41.0			45.0	
Minimum, preceding night, °F		24.0			19.0			10.0	
Atmospheric conditions		Light snow			Bright Sun			Bright Sun	

the ambient temperature is apparent in the upper ten inches of snow for January 30 and at nine inches for February 13 (Table 1). The apparent absorption of solar radiation is shown by the data for February 10, where a temperature of 37.6 F was recorded by the thermohms at a depth of two inches beneath the snow-surface. The thermocouple at the same depth and only a few inches distant from the thermohm shows a temperature of 32°F which, with an air-temperature of 41°F at the time, might be expected.

For all depths greater than ten inches below the snow-surface and for soil-temperatures, there is excellent agreement between thermohms and thermocouples.

Data on snow-temperatures, which have been obtained from two to four times each week, and occasionally several times each day, since January 1, indicate that it will be necessary to make thermal-quality determinations at frequent vertical intervals within the snow-pack at Soda Springs for satisfactory snow-melt analyses, unless the gradient shifts to a lower temperature than now being observed, before the melt-period begins. The persistency of temperatures within the snow-mantle of 32°F, at this time, indicates that the capillary water-content of the snow may be highly variable. The persistency of such temperatures, despite many nights of below-zero temperatures, shows the high insulation capacity of the snow.

The soil beneath the trellis supporting the temperature-measuring equipment was frozen to a depth of eight inches in late December previous to the arrival of permanent snows. A temperature of 27.5F was obtained by mercurial thermometer in the frozen portion of the soil. After the establishment of the permanent snow-cover, the soil-temperature rapidly rose to 32°F and has remained at that or slightly higher temperatures down to one foot below the surface, to date.

Soil-moisture, which is being determined by use of standard Bouyoucos plaster blocks and a standard Bouyoucos bridge, has been at 42 to 45 per cent since January 1. This would appear to indicate that the soil is fully primed and with temperatures of 32°F so persistent within the snow-pack there may be a constant accretion of water from melting snow to the soil which in turn may be contributing directly to stream-runoff during the winter months.

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Soda Springs Cooperative Snow-Research Project,
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A LATERAL SNOW-SAMPLER

R. A. Work, R. W. Childreth, and W. T. Frost

In forecasting stream-flow to be expected from a measured snow-supply in any given year, Oregon Water Forecast Committees have, in the past, been compelled to speculate upon the effect of structure and texture of snow upon water-accumulating power and water-releasing speed of the snow-pack. There have been questions as to why a greater water-yield some years than others is secured from approximately the same volume of mountain-stored snow.

To secure data bearing on these and other questions, a continuing experiment was initiated at Crater Lake National Park, Oregon, in 1940. This experiment is cooperatively conducted by the Soil Conservation Service, National Park Service, and the Oregon Agricultural Experiment Station. As a part of the study, observations of snow-density changes were made at the original midpoints of numerous superimposed snow-layers.

The sampler first devised for securing complete lateral snow-cores without digging secondary trenches, consisted of two sections of Federal snow-tubing screwed together. A strip of cold-rolled steel 1/2 inch by 1/16 inch held alongside the tube by three aluminum collars, one at either end and one in the middle, was free to slide through slots in the collars. When this strip was pushed forward, a slanting slot cut through the tube and cutting-point allowed the spring-steel point of the strip to advance into the snow-core at the forward end of the snow-tube. A one-quarter inch wide red band painted around the sampler 55 inches from the cutting-point tip indicated when the sampler had been driven this preselected distance. After the tube was forced into the snow this distance, the cut-off strip was pushed forward and the tube given one complete rotation, thus cutting the core completely free of the mass of snow. The tube and contained core were then withdrawn and weighed and density of the contained snow-core computed. Before taking each sample, the spring-steel cut-off was backed up until its tip was barely withdrawn from the inner circumference of the snow-tube cutting-point. This sampler worked very well in soft snow, but because of the resistance offered to penetration of the large aluminum collars, it was difficult to push evenly into frozen snow. It also left a very large hole to be back-filled.

An improved sampler was then made from a single 60-inch section of Mt. Rose steel tubing. The large collars used on the aluminum sampler were unnecessary, as small push bar steel guides could be, and were, brazed to the steel tubing. A Utah cutting-point (inner diameter 1.485 inches), substituted for the Mt. Rose point (inner diameter 1.5 inches), permitted use of a Utah-type scale for weighing either sampler. Details of this improved sampler, called the "Crater Lake lateral snow-sampler", are shown in Figures 1 and 2. The sampler in use is illustrated in Figure 3.

One hundred and fifty-two lateral samples, in snow ranging in density from 19 to 56 per cent, were taken with this sampler over a period of 6-1/2 months. In 134 out of 152 lateral 55-inch drives, the sampler cut and kept cores not less than 95 per cent the length of the sampler-drive. No difficulty at any time was experienced with the sampler sticking or clogging. The instrument may then prove useful in other locations for studies similar to ours.

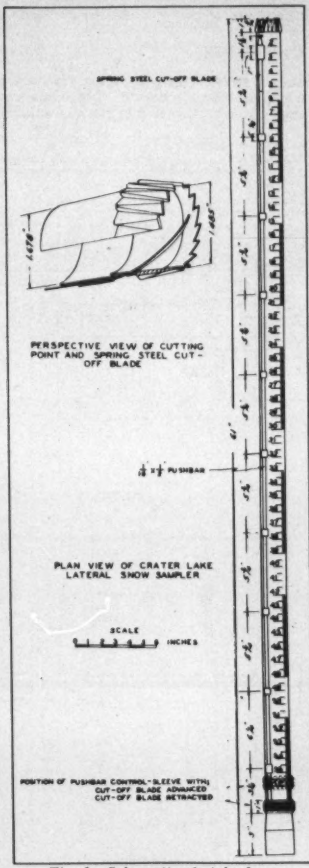
SPRING STEEL CUT-OFF BLADE
PERSPECTIVE VIEW OF CUTTING POINT AND SPRING STEEL CUT-OFF BLADE
PUSHBAR
PLAN VIEW OF CRATER LAKE LATERAL SNOW SAMPLER
SCALE
INCHES
POSITION OF PUSHBAR CONTROL-SLEEVE WITH CUT-OFF BLADE ADVANCED
CUT-OFF BLADE RETRACTED

Fig. 1--Schematic sketch of snow-sampler

Fig. 2--Crater Lake lateral snow-sampler

Fig. 3--Crater Lake lateral snow-sampler in use (snow-cores used to back-fill sample holes shown in foreground)

U. S. Soil Conservation Service and
Oregon Agricultural Experiment Station,
Medford, Oregon

A STEEL PIPE-CLIMBER

R. A. Work and R. W. Childreth

Most of the Federal-State cooperative snow-courses in Oregon are now permanently marked at end-points and tangent-intersections by two-inch iron pipes set in concrete. These pipe-markers, painted in alternating two-foot wide red and yellow stripes, are surmounted by the conventional yellow and black snow-course-marker signs.

Course-marker signs occasionally need replacement and pipe-markers sometimes require

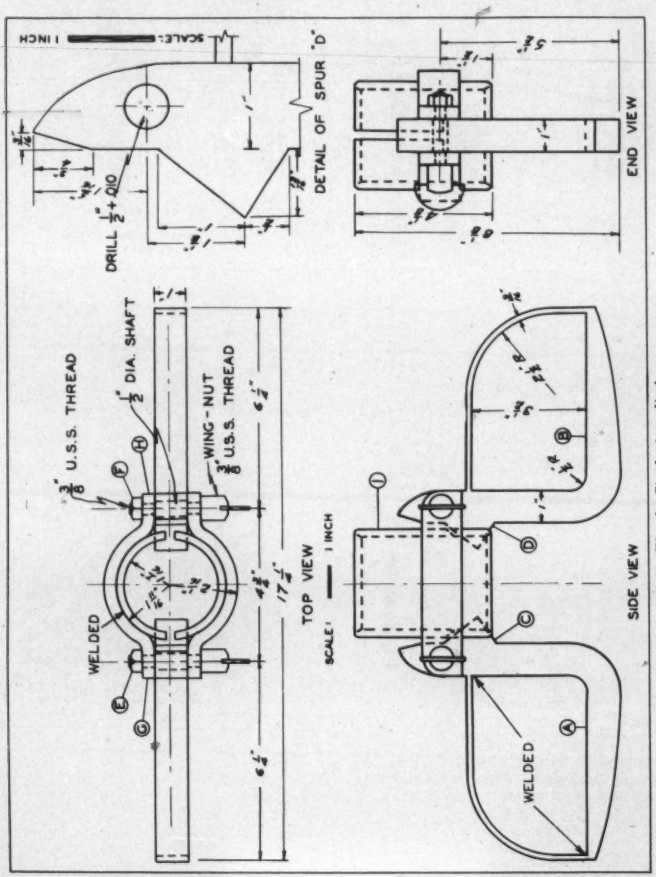

Fig. 1.--Steel-pipe climber

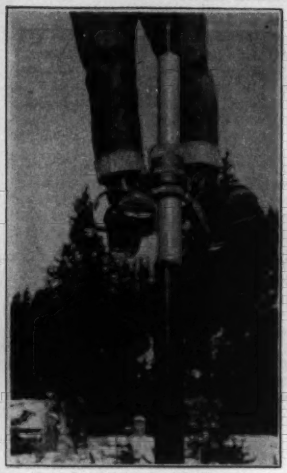

Fig. 2--Steel-pipe climber in use on two-inch pipe

repainting. Some type of portable climber is, therefore, required to expedite and make safe such work on pipes extending as much as 22 feet above the ground-surface. A climber meeting these requirements was developed by the authors in 1939 and has been used satisfactorily since that time.

The climber, detailed in Figure 1, consists essentially of two steel stirrups, A and B, each having an edged spur, C and D, facing inward toward the pipe. Both stirrups pivot on short steel shafts, E and F, which are each secured at one end to opposing nibs, G and H, on the split cylindrical steel sleeve I, which encases any two-inch pipe to be climbed.

In assembling the climber for use, stirrups A and B are slipped onto the steel support shafts E and F, with the stirrup-spurs C and D facing each other. The stirrups are then lifted upward and outward as far as possible and the partly assembled climber placed on the iron pipe. The weight of the stirrups levering on shafts E and F then exerts sufficient pressure through the spurs against the pipe that the climber will remain as placed without further support, while the remaining one-half of the split steel sleeve I is slipped in place over the threaded ends of shafts E and F. This half-sleeve is held in firm contact with the opposing half of the sleeve by means of threaded wing-nuts screwed onto the threaded ends of shafts E and F.

In using the climber, one foot is placed in each stirrup. The operator then grasps the pipe to be climbed above his head with both hands and, hooking the toes of his shoes under the stirrup-hoods, draws both feet upward, bringing the climber with them. Placing the weight of the body on the stirrups with the climber in a new position, holds it in place while a new and higher hand-grip is secured.

To facilitate passage of the climber over two-inch pipe couplings, the inside diameter of the split steel sleeve is slightly greater than the outside diameter of any two-inch pipe coupling likely to be encountered. Thus, the inner diameter of the split sleeve is considerably greater than the outside diameter of ordinary two-inch iron pipe. This imparts a slight rocking motion to the climber if weight of the body is shifted from one foot to the other when working on a pipe-section. However, we did not find this to reduce the safety of the climber. The climber in use is shown in Figure 2. No doubt the climber would be even more portable if certain parts were made of light-weight alloy metal, thus reducing its weight. The described climber, all of steel, weighs 11 pounds.

U. S. Soil Conservation Service and
Oregon Agricultural Experiment Station,
Medford, Oregon

DISCUSSION

FRED PAGET (State Division of Water Resources, Sacramento, California)--Mr. Work's discussion of his ingenious device for climbing his pipe snow-course markers moves me to put in a word or two for the lowly ladder. Under many situations it has a definite place. On maintenance work of the California Cooperative Snow-Surveys much use is made of the ladder.

Most of our snow-course markers in California are placed on trees at the margin of open meadows. Some of the trees can be climbed easily when the branches reach down to the ground. On others where the lowest limb is beyond the reach of a standing man, or where there are no limbs at all (see Fig. 1), the ladder is much handier for the untrained man than a pair of pole-climbers.

Fig. 2--Light 12-foot ladder carried handily on regular ski-rack, Lassen National Park, August 6, 1941

Fig. 1--Using 12-foot ladder to place snow-course marker

By using 12-foot ladders that are light and easy to carry, three men recently placed trail-marker signs along five miles of trail in one day with the signs averaging 80 feet apart and 16 feet high. Each man had a ladder. The ladder is easily carried from job to job on a ski-rack on top of the car (see Fig. 2).

SNOW-CONFERENCE, MORNING SESSION, FEBRUARY 19, 1944

ADJUSTING FORECAST CURVES FOR ABNORMAL SPRING AND SUMMER TEMPERATURES

R. A. Work

Introduction

With 20,000,000 acres under irrigation in Western States, the importance of the contribution of agricultural irrigation to the Nation's production of food and to fighting this war is clearly defined. It should be similarly recognized that irrigated lands have special problems not common to all farm-lands. One problem is the determination and proper management of available water-supply. Just as any industrial concern, to meet schedules of production, must correctly inventory at all times its raw materials on hand or available, so must irrigation enterprise prepare daily, monthly, and annual inventories of water-supplies on hand or in prospect. These inventories in Western States are known under the general term of snow-surveys and are frequently so inclusive as to encompass measurements of the volume of water impounded in reservoirs, in the mountain snow-cover, in watershed and crop-land soils, and in subterranean storage both on the watersheds and beneath the cultivated valleys below. The snow-surveys include the collection of data intended to indicate what proportion of such water-supplies may be available for use.

In years of deficient snowfall the water-supply forecasts based on snow-surveys tend to emphasize the short water-supply in prospect. Farmers accordingly can plan to curtail irrigated acreage or plant more than usual acreage to early maturing crops. In such years crops of lower water-requirement may be planted, or immediate attention may be given to quickly developing a supplemental water-supply by storage or diversion or by pumping of hitherto unused water-supplies either surface or subsurface.

In years of great snowfall-accumulation particular emphasis in the water-supply forecasts may be placed on the abundance of water to be expected rather than on any possible shortages. As a result a great many water-storage reservoirs may be used as flood-control structures, to regulate stream-flows so far as possible, to reduce flood-crests, and yet insure safe and maximum storage-contents for later irrigation. The snow-surveys are of real value to flood-control and levee districts, and to some industrial plants located on streams where high spring flood-flows occur from melting snow, inasmuch as advance warning allows preparations which result in a minimum loss of crops, material, and time from high riv[illegible]-stages.

Of equal importance with food is a sustained impressive flow of munitions and materiel of war to supply our fighting men on far-flung battle fronts. The success of our war effort in a large measure depends on how much electric power may be available to drive production machinery. Correct estimation of water to be available to drive power-turbines is essential to maximum economic power-production and to the coordination of distribution of electrical energy over the interconnected network of high-tension distribution-lines.

With each year of additional record, snow-surveys become of greater use in forecasting probable stream-flow. In many drainage-basins the length of record still is relatively short and it must be agreed that in such cases empirical methods of adjusting snow-survey records to explain deviations of forecast from obtained flow are subject to some criticism on the basis that records are of insufficient length to fully justify assumption of repetition of behavior. On the other hand, water-users expect the quickest possible use of snow-survey data and cannot wait indefinitely for initiation of water-supply forecasts. It is the experience of most engineers in this field that rarely are there enough years of record on which to base the perfect picture of watershed-behavior. Methods of forecast most likely to stand the tests of time and usage are those based on observation of cause and effect, best possible understanding of the watershed hydrologic cycle, and most accurate adaptation of existing data. Factors limiting their most successful development are incomplete hydrologic and climatological data in the watersheds, and, as mentioned, records of relatively short extent.

Factors affecting the snow-runoff relationship

Much attention in recent years has been focused upon the factors which disturb the snowfall-runoff relationship. It is conceded generally that any one or combinations of the following factors influencing this relationship may account for failure of forecasted discharge to agree closely with the value of measured discharge:

(A) Incorrect stream-discharge record
(B) Incorrect snow-survey record
(C) Watershed-precipitation departure from normal during the runoff-season and especially during the month or months of peak-runoff--Above-normal precipitation at such times tends to increase runoff and below-normal precipitation tends to reduce runoff.
(D) Watershed-precipitation departure from normal the preceding fall, as it affects restoration of watershed soil-moisture, frequently affects runoff the following year--Snow on dry soil is less effective in creating stream-flow than the same amount of snow on wet soil.
(E) Percentage of the total winter precipitation occurring at the snow-course level as snow--If a small percentage falls as snow, as might be the case in a warm winter, the watershed may be better wetted than usual under the snow remaining on April 1 and should deliver a greater water-yield than indicated by the snow-survey alone. The reverse may occur in a cold winter of low precipitation.
(F) Relatively greater or lesser snowfall at other watershed-levels than reflected by a high or low elevation snow-course alone--Relatively less snowfall at lower levels occurs in warm winters and relatively greater snowfall at lower levels occurs in cold winters. Therefore, snow-distribution according to elevations of watershed is not always comparable from year to year.
(G) Temperature of watershed during the runoff-period if above normal induces more rapid snow-melt and a more immediate and complete delivery of snow-melt to stream-flow, thus relatively increasing total runoff. Below-normal temperatures have a reverse tendency and a greater portion of the snow-blanket is dissipated by evaporation or other losses.
(H) Watershed-lag--The volcanic Cascade Range north of Mt. Lassen, California, is visibly characterized by prominent extrusions of lava and remnants of once-active volcanoes. The higher watershed-soils of pumice, ash, cinders, or disintegrated volcanic rock are often of great depth and permeability. The basalt supporting these beds of lava or pumice is often fissured and veined by underground caverns and grottoes capable of storing and

transporting a considerable volume of water. The area is further characterized by many streams entering visible surface existence as full-fledged flows whose underground origin may be distant from the visible source. Some man-made reservoirs annually lose large amounts of water by seepage into these subterranean channels. It is, therefore, believed that annual stream-flow, in this area at least, is determined to some extent by the amount of water held in subterranean storage and this in turn is determined not only by the preceding winter's precipitation but to an undetermined extent by that of the year or years going before.

The factors above are classed within either of two categories: (1) Factors which can be evaluated and applied to correct snow-survey data at time of forecast; (2) factors which cannot be evaluated as of April 1 and are therefore not effective in improving accuracy of the forecast for April 1. Factors in category (2) are useful later in explaining deviations between forecast and obtained flow and are of particular value in adjusting annual plottings of snow-cover and runoff to better define the mean forecast-curve. Factors included in category (1) are (D), (E), (F), and (H). Factors in category (2) include (C) and (G).

Correction-methods

PAGET [see 10 of "References" at end of paper] has suggested one method of correcting the forecast on April 1 of runoff to account for departures of precipitation from normal during the early runoff-period. CLYDE and WORK [2] showed factors (C) and (F) to be effective in modifying runoff of Big Cottonwood Creek, Utah, from amount forecast by snow-surveys of April 1 at one high-elevation snow-course.

CLYDE [1], EAGLE [3], FARROW [5], MARR [6], and MONSON [8] all have suggested methods of determining the status of watershed soil-moisture or correcting snow-survey data to account for watershed soil-moisture departures from normal [Factor (D)].

ELGES [4] discussed methods of watershed elevation-zoning and illustrated some methods of weighting water-content of snow at various elevation-zones to compensate for annual discrepancies in the forecast-curve due to factors (E) and (F). PAGET [11] also offered an informative statement relative to effect of Factor (F) in California in 1940.

McLAUGHLIN [7] recognized Factor (H) under the broad descriptive term of "Climatic trend", but apparently few experimental data are so far available bearing on the effect upon runoff of this factor, or describing methods of adjusting correlation-curves therefor.

OLSEN and PRICE [9] describe a method resulting in extremely accurate forecasts of net inflow to Upper Klamath Lake, Oregon. These authors stress importance of considering Factor (H) in calculating the seasonal runoff-factor for the watershed.

The purpose of this paper is to describe a method of adjusting the snow-survey results of April 1 when constructing the forecast-curve so as to compensate for temperature-deviations from normal during the runoff-season [Factor (G)]. This method was suggested from studies of Squaw Creek and Tumalo Creek drainage-basins in Oregon.

Description of Squaw Creek Watershed

Squaw Creek, an important tributary from the west to the upper Deschutes River, heads in the broken mountainous country on the east side of the Cascade Range between the North Sister and Broken Top. Maximum elevation of watershed is 10,354 feet (summit of South Sister). Several glaciers feed the stream at low flow. Flow of this stream is entirely diverted below the gaging-station for irrigation during the low-flow period.

Irrigation from Squaw Creek begins usually in early April and lasts through September. It is important then to forecast the probable flow of Squaw Creek for the April-September period in order that water-users may plan their crops and acreage accordingly, and particularly water-users under the Plainview and McCallister ditches securing water from Squaw Creek only after satisfaction of prior rights of the Squaw Creek Canal which diverts major portion of the stream-flow.

The gaging-station on this stream (No. 335) is above all diversions except a canal diverting the summer flow of Pole Creek, a tributary. In Oregon State Engineer Bulletin No. 7 (1924) it is stated that the diversion-canal from Pole Creek ". . . has been eroded until it carries the entire flow of this creek." Therefore, in planimetering drainage-area of the watershed on "Three

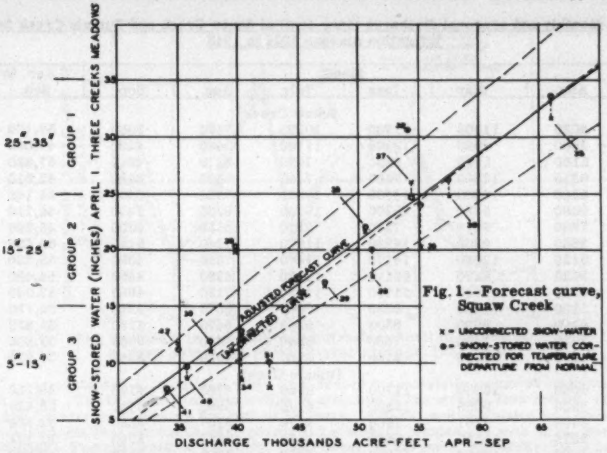

Fig. 1--Forecast curve, Squaw Creek

Sisters Quadrangle", Pole Creek Drainage-Area was excluded, and the computed area of 47.6 square miles compares with 63 square miles given in the State Engineer's report for Squaw Creek. Evidently the State Engineer included the Pole Creek Watershed. It is believed that flow-records at Station 335, at least since 1924, represent total flow of Squaw Creek minus Pole Creek.

Total area of watershed above the gaging-station (but not including the drainage-area of Pole Creek) is zoned according to elevations as follows:

Below 5000 feet	9.8 square miles	= 21 per cent of the area
5000-6000 feet	10.7 square miles	= 22 per cent of the area
6000-7000 feet	15.6 square miles	= 33 per cent of the area
Above 7000 feet	11.5 square miles	= 24 per cent of the area
Total	47.6 square miles	= 100 per cent of the area

Three Creeks Meadows Snow-Course (Sec. 3, T. 17 S, R. 9 E) is on the eastern edge of the drainage at elevation 5600 feet. New Dutchman, a nearby snow-course, is six miles south of the most southerly part of the Squaw Creek drainage at elevation 6400 feet. McKenzie, the only other nearby snow-course, is six miles west-northwest of the northwest corner of the Squaw Creek drainage and lies at elevation 4800 feet on the western slope of the Cascade Range. Snow-surveys on Three Creeks Meadows Course began in 1928 and are annually unbroken to date; whereas records on New Dutchman, which began in 1930, are broken and irregular; and records on McKenzie, while unbroken, date back to only 1939.

In seeking a method of forecasting flow of Squaw Creek from the existing snow-surveys it was believed best results might be obtained, for the time being, by using records from Three Creeks Meadows Snow-Course alone as the greatest length of record is available there. At some future date, as longer records accumulate on the nearby New Dutchman and McKenzie snow-courses, refinements should be possible to the forecast-method proposed in this paper.

Forecasting flow of Squaw Creek

The discussion to follow would be more complete if correction methods could be shown to account for all of the disturbing factors outlined in (A) to (H). Furthermore, the perfect correlation-technique depends on fitting each of these factors into its proper niche in relationship to the others and to the seasonal runoff. Such comprehensive development is not attempted in this paper for reasons which will be later explained in some detail.

Figure 1 demonstrates graphical correlation of the snow-cover of April 1 at Three Creeks

Table 1--Monthly and seasonal discharge (acre-feet) of Squaw Creek and Tumalo Creek for irrigation seasons 1928 to 1942

Year	Month						Apr. to Sep.
	Apr.	May	June	July	Aug.	Sep.	
				Squaw Creek			
1928	4020	11900	11700	10800	7690	5060	51,170
1929	2200	7320	12100	11700	9470	4290	47,080
1930	5160	5720	8330	7930	6270	4210	37,620
1931	6310	12200	7680	7440	5460	3420	42,510
1932	5380	10600	14700	10900	7560	5000	54,140
1933	3690	5830	23200	18700	9220	5470	66,110
1934	7890	8410	7570	7170	5650	3800	40,290
1935	3650	9260	14280	11070	7240	5150	50,650
1936	6130	12010	14170	11470	7050	4390	55,220
1937	3420	8570	19170	12520	6360	4450	54,490
1938	6260	11540	15790	11930	7130	4880	57,530
1939	5100	11220	8020	7060	5070	3240	39,710
1940	4270	8090	9300	6300	4470	3180	35,610
1941	2930	7490	7680	6840	5380	3580	33,900
1942	4090	6330	8100	8160	4910	3360	34,950
				Tumalo Creek			
1928	5050	15900	11700	6580	4760	4120	48,110
1929	3500	9050	12500	6170	3960	3440	38,620
1930	6709	7261	7500	4479	3267	3090	32,306
1931	5856	11556	5620	3470	2930	2740	32,172
1932	4500	13100	15900	8870	4250	3370	49,990
1933	4070	6120	22580	14030	5500	4550	56,850
1934	8877	8230	6164	4680	4010	3170	35,131
1935	4250	11290	14400	8930	4470	3498	46,838
1936	7660	14300	14030	7030	4180	3468	50,668
1937	3490	8988	18390	7390	3562	3100	44,920
1938	6332	13540	16110	8080	4160	3570	51,792
1939	6720	11290	8120	5371	3360	3006	37,867
1940	5750	10470	7770	3950	3360	3360	34,660
1941	4470	9430	7140	4130	3330	3470	31,970
1942	4860	7550	10240	4870	3000	2810	33,330

Meadows with subsequent six-month discharge of Squaw Creek. In preparing this chart the uncorrected forecast-curve was eyed among the scattered plottings as a best-fit straight line.

Study of the chart shows that without adjustment of the data, or correction for annual climatic deviations or abnormalities of watershed, six of the 15 plottings vary from the uncorrected forecast-curve by amounts greater than ten per cent and average deviation of 15 plottings is 8.2 per cent, assuming the mean curve as 100. The greatest deviations occurred in 1931 when the divergence of obtained flow from the amount forecasted from the mean curve was 23.2 per cent, and 1939 when the divergence was 19.8 per cent. According to the classification proposed by WORK and RYAN [12], forecasts which might have been obtained in 15 years by use of this curve rank as follows:

Classification	Number	Per cent of total
Excellent	8	53
Good or better	9	60
Fair or better	14	93
Poor	1	7

Use of the uncorrected forecast-curve in Figure 1 would result in forecasts for April 1 which are 90 per cent correct or better in a little over one-half of the cases. Consideration should evidently be given to the reasons for failure of more of the forecasts to measure up to at least a "good-or-better" classification.

Monthly and seasonal discharge of Squaw Creek for irrigation-seasons of 1928-42 is shown in Table 1. Examination of the discharge-records of Squaw Creek from 1928 to date indicates no obvious errors. In general the stream-flow records are classed as good (90 per cent correct or better) except for some estimation in short winter periods of ice-effect or short summer periods

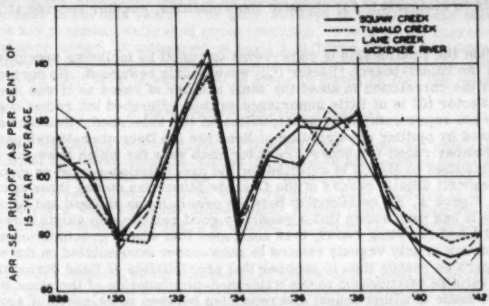

Fig. 2--Runoff of some adjoining streams, April to September, each as percentage of its 15-year average, 1928-1942

of missing gage-heights. It is doubtful if the flow-record is materially impaired by inclusion of these estimates. To obtain further verification of accuracy of the stream-flow record, the Squaw Creek April-September discharge for each of 15 years, 1928-42, was calculated as a percentage of the mean six-month flow for the 15-year period and plotted in comparison with three other adjacent streams--Tumalo Creek on the south, Lake Creek on the north, and McKenzie River on the west. These comparisons plotted in Figure 2 indicate no notable abnormality of discharge for Squaw Creek during the April-September period in any year.

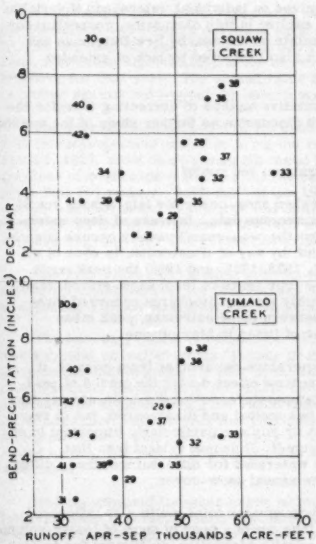

Fig. 3--Winter precipitation at Bend versus runoff following spring and summer of some nearby streams

Examination of the Three Creeks Meadows Snow-Survey records shows no evident error. Most of the surveys were obtained by A. E. PERRY, Watermaster of Deschutes County, a skilled snow-surveyor, and appear accurate in all respects. Plotted coordination for years of record of New Dutchman snow-surveys of April 1 with Squaw Creek runoff shows approximately the same yearly relationship of New Dutchman Course snow to runoff as Three Creeks Meadows Course snow to runoff. Therefore, the Three Creeks Meadows snow-surveys are assumed to correctly represent snow-conditions on that course on about April 1 of each year.

Climatological data

Major winter storms providing moisture to this watershed come from the west, crossing the Cascade Mountains and funneling through the mountain passes. The greater part of the moisture is condensed and precipitated on the Cascade western slopes, with decreasing amounts deposited as the storms move east from the Cascade Divide. There are no climatological stations in this watershed and the nearest valley weather station on the Eastern Cascade slope is at Bend, elevation 3623 feet and 16 miles east of the east boundary of the watershed. On the western slope the nearest climatological observations are taken at McKenzie Bridge, elevation 1372 feet and 18 miles west of the western boundary of Squaw Creek Watershed. Weather records at Bend date to 1902. McKenzie Bridge climatological records lapsed from January, 1914, to December, 1936; therefore, in developing various adjustments of

the snow-survey data to compensate for climatic abnormalities, weather records at Bend were used.

Attempts to adjust the relationship of snow-cover to runoff by including precipitation-departures from normal during the runoff-season [Factor (C)] were poorly rewarded. No correction was found which did not impair the correlation in about the same number of years as it was improved. This does not mean that Factor (C) is of little importance on this watershed but rather suggests that precipitation at Bend is not representative of precipitation on the watershed. Evidence supporting this suggestion is furnished by plotting precipitation at Bend for the December-March period against following April-September runoff for Squaw Creek for each year for which snow-surveys are available. The period December to March is selected for the precipitation-period as much the greater part of the annual snowfall usually occurs in the Cascade Mountains during those months. This plotting is shown in Figure 3. No relationship between precipitation at Bend and Squaw Creek runoff is evident. Since it has been shown that a generally good relationship exists between watershed snow-cover of April 1 and resulting runoff, it is concluded that winter precipitation at Bend within this time-envelope shown is only vaguely related to snow-cover accumulated on the watershed by April 1. There appears no reason then to suppose that precipitation at Bend during the runoff-season will bear any more definite relationship to the watershed-precipitation of the same time-period. Futile attempts were made to adjust annual discrepancies between snow-cover of April 1 and subsequent discharge of Squaw Creek by applying Factor (C) corrections from records of precipitation at Eugene, Leaburg, and Oakridge--other western Cascade slope stations.

Lack of proper records with which to explore Factor (C) similarly hampers exploration of Factor (D). Precipitation, so far as it affects soil-moisture, can be at best only an indirect measure of resultant soil-moisture. Some hydrologists incline to the opinion that direct determination of soil-moisture is the better plan. This has not been accomplished to date on the Squaw Creek Watershed.

Snow-courses at both high and low elevations are required on individual watersheds if variable Factor (E) is to be satisfactorily evaluated. As indicated earlier in this discussion, correction for Factor (E) may become possible as longer records accumulate on the nearby New Dutchman and McKenzie snow-courses. Full exploration of Factor (F) is also hampered by lack of extended records at these other snow-courses.

So far as watershed-lag Factor (H) is concerned, a tentative method of correcting therefor has been developed for Squaw Creek, but is not included in this discussion as further study of the method is desired.

Relationship of snow-cover, temperature, and runoff

It is commonly observed that in years of scanty watershed snow-cover the late-season runoff is not only deficient but peaks in volume at an earlier than average date. In years of deep watershed snow-cover the resultant runoff is not only greater but the peak-runoff usually occurs later in the spring or summer seasons. On Squaw Creek Watershed, by way of illustration, in each of the four years of greatest snow-stored water on April 1 (1932, 1933, 1937, and 1938) the peak mean monthly stream-discharge occurred in June. In each of the four years of least snow-stored water on April 1 (1931, 1934, 1940, and 1941) the peak mean monthly stream-discharge occurred three times in May and once in April. In years of snow-cover between these extremes, peak mean monthly stream-discharge occurred about an equal number of times in May or June.

In considering the effect upon runoff of watershed temperature-departures from normal, it seems logical to assume that such departures will be of greatest effect during the period of peak-runoff. In years of deficient snow-cover and early melt, temperature-deviations from normal during June or July can have no effect upon snow that already has melted and disappeared, but in years of heavy snow-cover, high or low air-temperatures in June or July are particularly important in affecting the rapidity of snow-melt and volume of resulting runoff. It seems evident then that correction-factors for temperature must be applied to the watershed for different months in different years depending upon the volume and areal extent of the annual snow-cover.

A snow-cover of large volume and areal extent will show greater total melting as influenced by a mean monthly temperature-departure of, say, +5° F, than would a body of snow of lesser volume and areal extent. This being true, it will be necessary to adopt a correction-coefficient for temperature of greater magnitude for a large volume of snow than for a smaller volume of snow, since the measurement of applied accuracy of the corrective coefficient is total volume of melt-water discharge.

On the Squaw Creek Watershed there is no direct measure of the percentage of the watershed-area covered by snow in various years. The snow-surveys at Three Creeks Meadows Snow-Course must provide the key to annual watershed snow-coverage. It is believed correct to assume that in years of shallow snow-cover, as measured on April 1 at Three Creeks Meadows Course, a lesser percentage of the watershed is snow-covered than in years of abundant snow-stored water, as about one-third of the total area of watershed is lower in elevation than the snow-course.

A temperature-correction method

In developing a temperature-correction for Squaw Creek runoff, the snow-survey years of record were grouped into three classes: Group (1) including all years in which the snow-stored water on April 1 at Three Creeks Meadows Course ranged in depth from 25 to 35 inches; group (2) including those years when the snow-stored water ranged in depth from 15 to 25 inches; and group (3) including those years when the snow-stored water ranged in depth from five to 15 inches. Each of the latter two groups included six years of record, but group (1) included only three years of record.

June and July were selected as the months when temperature-departures from normal affect total runoff to the greatest extent in years of group (1), since peak-runoff occurred in all these years in June, and average runoff in July was greater than that in May.

May and June were selected as the key months when temperature-departures from normal most greatly affect runoff in years of group (2), since peak-runoff occurred in three of the six years in May and in remaining years in June.

April and May were selected as the key months when temperature-departures from normal show the greatest effect in influencing runoff in years of group (3), as peak-runoff occurred in the majority of these years in April or May.

Total temperature-departures from normal (normals are based on 41 years of record at Bend) for the selected two-month period of each year in each group were multiplied by 1.0 in group (1), by 0.66 in group (2), and by 0.33 in group (3). Each resultant, given the same sign as its multiplicand, was added algebraically to the snow-stored water (inches) on April 1 at Three Creeks Meadows for that year. The annual value of snow-stored water (inches) on April 1 thus corrected is plotted against subsequent six-month stream-discharge in Figure 1.

The correction-coefficient of 1.0 used for group (1) is purely arbitrary and was selected as that correction-value tended to bring the values for snow-stored water of April 1, 1933, and April 1, 1937, most closely onto the mean forecast-curve. The year 1932 was not affected, regardless of coefficient-value, as the temperature-departure was zero, so it seems that factors other than (G) make a "hold-out" of the 1932-plotting. The correction-coefficient for groups (2) and (3) was then set at two-thirds and one-third, respectively, of the correction-coefficient for group (1), as the snow-volumes involved were presumed roughly in those proportions to snow-volumes in group (1). The correction-computations are illustrated in Table 2.

The very close relationship between daily mean air-temperature and mean daily stream-discharge in second-feet for this stream is shown in Figure 4. Also shown in Figure 4 is discharge of adjoining Tumalo Creek for the important months of irrigation.

The following points in connection with this thermo-hydrograph may be worthy of note: 1932 was a typical so-called group (1) year of maximum snowfall and later than usual runoff; 1931 was a typical so-called group (3) year of minimum snowfall and early runoff. Limitation of space precludes similar plotting of other years, but the illustrated years appear quite typical. Precipitation as measured at Bend during the runoff-season appears to have had relatively small effect on runoff at any time in either year and certainly much less effect than the accumulated snow as affected by temperature. This also was the case in most of the other years not illustrated here. As mentioned before, the record of precipitation at Bend does not seem to parallel precipitation on the watershed.

Had the adjusted forecast-curve shown in Figure 1 been available in 1928 and had temperatures following date of forecast each year been normal, the average annual error of forecast in the 15 years following would have been 5.3 per cent and, in 11 of the 15 years, forecasts would have rated "excellent" (95 per cent correct or better). In 12 of the 15 years, forecasts would have rated "good or better" (90 per cent correct or better). In all other years, forecasts would have rated "fair or better" (80 per cent correct or better). It is true that corrections based on climatic ab-

Table 2--Relation snow-cover to runoff and temperature-departure corrections, Squaw Creek

No.	Snow-water range Apr. 1	Year	Water-content snow Apr. 1[a]	Monthly mean temperature-departure from normal at Bend, Oregon					Corr'n coef-ficient[b]	Cor-rec-tion[c]
				Apr.	May	June	July	June-July		
	in		in	°F	°F	°F	°F	°F		in
1	25-35	1933	31.7	-0.4	-4.8	0.0	+2.0	+2.0	1.0	+2.0
		1932	30.6	+0.6	+0.4	+2.4	-2.4	0.0	1.0	0.0
		1937	26.1	-1.7	-0.2	-1.2	-0.2	-1.4	1.0	-1.4
								May-June		
2	15-25	1938	24.6	-0.4	+0.8	+1.6	+2.8	+2.4	0.66	+1.6
		1935	21.7	-1.0	0.0	+0.6	-0.8	+0.6	0.66	+0.4
		1936	20.2	+4.8	+4.2	+1.6	+0.8	+5.8	0.66	+3.8
		1939	19.9	+4.8	+3.3	-2.6	+2.0	+0.7	0.66	+0.5
		1928	17.6	-2.1	+5.8	-2.2	+1.0	+3.6	0.66	+2.4
		1929	16.8	-3.8	+1.1	-0.7	+1.2	+0.4	0.66	+0.3
								April-May		
3	5-15	1942	11.8	+0.8	-2.5	-5.0	-0.2	-1.7	0.33	-0.6
		1930	11.0	+5.0	-2.0	-1.8	+0.2	+3.0	0.33	+1.0
		1940	8.7	+0.7	+2.2	+0.4	-1.9	+2.9	0.33	+1.0
		1934	8.5	+8.4	+5.0	-1.0	+0.2	+13.4	0.33	+4.4
		1931	7.8	+1.6	+5.4	-0.8	+2.6	+7.0	0.33	+2.3
		1941	7.5	+0.2	+0.3	-3.4	+0.2	+0.5	0.33	+0.2

No.	Adj. water-content snow Apr. 1	April-Sep. dis-charge	Uncor-rected Apr.-Sep. forecast	Obtained as per cent of forecast	Devia-tion from 100	Adj. Apr.-Sep. forecast	Obtained as per cent of forecast	Devia-tion from 100
	in	ac-ft	ac-ft	pct	pct	ac-ft	pct	pct
1	33.7	66,110	64,000	103.3	3.3	66,600	99.3	0.7
	30.6	54,140	62,600	86.5	13.5	62,600	86.5	13.5
	24.7	54,490	57,200	95.3	4.7	55,000	99.1	0.9
2	26.2	57,530	55,400	103.8	3.8	57,000	100.9	0.9
	22.1	50,650	51,700	98.0	2.0	51,600	98.2	1.8
	24.0	55,220	50,000	110.4	10.4	54,100	102.1	2.1
	20.4	39,710	49,500	80.2	19.8	49,400	80.4	19.6
	20.0	51,170	46,600	109.8	9.8	49,000	104.4	4.4
	17.1	47,080	45,700	103.0	3.0	45,200	104.2	4.2
3	11.2	34,950	39,500	88.5	11.5	37,250	93.8	6.2
	12.0	37,620	38,500	97.7	2.3	38,500	97.7	2.3
	9.7	35,610	35,500	100.3	0.3	35,500	100.3	0.3
	12.9	40,290	35,200	114.5	14.5	39,600	101.7	1.7
	10.1	42,510	34,500	123.2	23.2	36,150	117.6	17.6
	7.7	33,900	34,000	99.7	0.3	32,750	103.5	3.5
			Mean	....	8.2	.....	...	5.3

[a] At Three Creeks Meadows Course. [b] For application to temperature-departure. [c] For application to water-content of snow on April 1.

normalities occurring in months following issuance of water-forecasts for April 1 can be of little or no benefit at the time seasonal forecasts are issued. This does not constitute valid reason for rejecting such corrections, because, at a later date, when adjusting seasonal plottings on which forecast-curves are based, abnormal conditions affecting runoff in any month of the forecast period must be considered.

Future forecasts based on this adjusted curve should, on the average, be no less accurate. With maturity of the New Dutchman and McKenzie snow-survey records, improved curves and closer forecasting are to be expected.

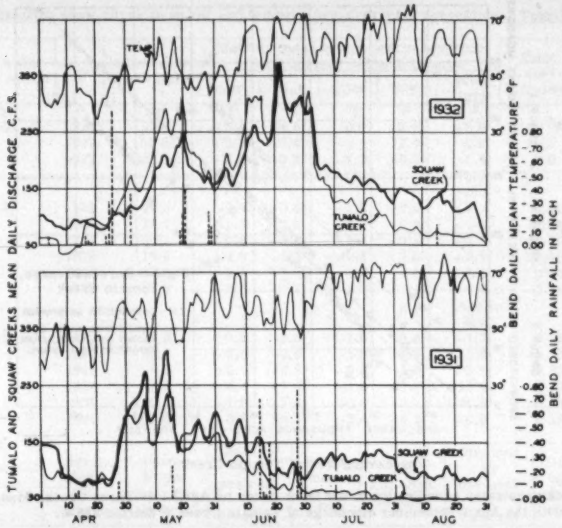

Fig. 4--Runoff in relation to watershed air-temperature

Description of Tumalo Creek Watershed

This stream originates in the high mountainous plateau sloping east from Broken Top Mountain on the eastern Cascade slope immediately south of and adjoining the Squaw Creek Drainage. Maximum elevation of watershed is approximately 9200 feet. Water-flow of this stream is diverted both above and below the gaging-station for irrigation of lands between Bend and Sisters. This stream also is source of municipal water-supply for the City of Bend.

The gaging-station on this stream (No. 338) is below the intake to the Columbia Southern Canal. A stream gaging-station (No. 334) is maintained on the Columbia Southern Canal about a mile below the head-gate. The combined flow of stations 338 and 334 is, therefore, used to indicate total discharge of Tumalo Creek. The combined value is identified under Station No. 338-a and only those combined discharges are used in developing snow-runoff correlation-curves for Tumalo Creek.

Total watershed drainage-area above the gaging-station (No. 338) is planimetered on the "Three Sisters" and "Bend" quadrangle-sheets as 55.2 square miles, elevation-zoned as follows:

Below 5000 feet	15.5 square miles =	28.1 per cent of the area
5000-6000 feet	15.3 square miles =	27.7 per cent of the area
6000-7000 feet	16.6 square miles =	30.1 per cent of the area
Above 7000 feet	7.8 square miles =	14.1 per cent of the area
	55.2 square miles =	100 per cent of the area

Three Creeks Meadows Snow-Course is about three miles north of the north side of the drainage and New Dutchman Snow-Course is about one mile west of the southwest edge of this drainage. There is no snow-course directly on Tumalo Creek Drainage. It is believed, for the time being at least, as with Squaw Creek, that best forecasts may be obtained through use of records for Three Creeks Meadows Snow-Course as the greatest length of record is available there. At some future date, as records mature on the nearby New Dutchman Snow-Course, it seems possible that averaging the records of the Three Creeks and New Dutchman courses, by a system of zoning and weighting, may result in the most accurate forecast-curve.

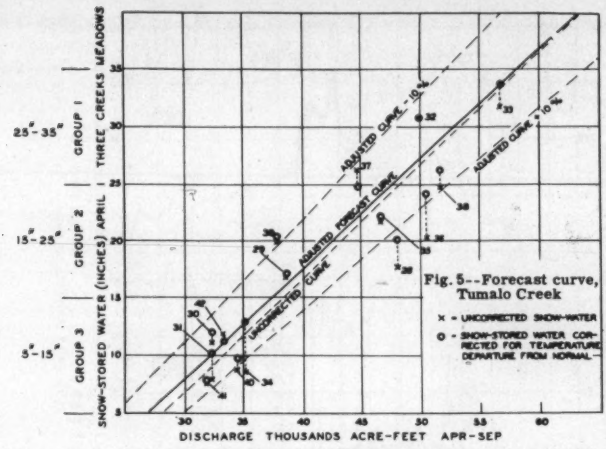

Fig. 5--Forecast curve, Tumalo Creek

Forecasting flow of Tumalo Creek

Figure 5 demonstrates coordination of the snow-cover on April 1 at Three Creeks Meadows Snow-Course with the April-September discharge of Tumalo Creek at Station 338-a.

Study of the chart shows that without further adjustment of the data, or correction for annual climatic deviations or abnormalities of watershed, four of the 15 plottings vary from the forecast-curve by amounts greater than ten per cent and the average deviation for 15 plottings is 7.9 per cent, assuming the correlation-curve as 100. According to the classification [12] previously mentioned, forecasts which might have been obtained in 15 years by use of this forecast-curve rank as follows:

Classification	Number	Per cent of total
Excellent	6	40
Good or better	11	73
Fair or better	15	100
Poor	0	0

The temperature-correction method developed for the Squaw Creek Drainage-Area was applied to Tumalo Creek with encouraging results as shown in Table 3 and in Figure 5. Had the adjusted forecast-curve of Figure 5 been available from 1928, the average annual forecast-error in the 15 years following would, under normal conditions of temperature, have been 5.3 per cent. In 13 of the 15 years, forecasts would have rated "good or better" (90 per cent correct or better). In no year would any forecast have rated "poor". Of the 15 forecasts, 12 were improved and three were impaired by application of the temperature-correction.

Only in rare cases do empirical correction-methods improve all years in the relationship. In some years, other factors may out-balance the factor for which correction is sought. This does not necessarily discredit any particular correction but rather stresses the importance of developing best possible understanding of each year's behavior of each individual watershed.

The method suggested herein for correcting seasonal relationships of snow-cover to runoff to account for abnormalities of temperature would rest on the best basis of proof if adopted and used to improve forecast-curves on other watersheds.

Table 3--Relation snow-cover to runoff and temperature-departure corrections, Tumalo Creek

No.	Snow-water range Apr. 1	Year	Water-content snow Apr. 1[a]	Monthly mean temperature-departure from normal at Bend, Oregon					Corr'n coef-ficient[b]	Cor-rec-tion[c]
				Apr.	May	June	July	June-July		
	in		in	°F	°F	°F	°F	°F		in
1	25-35	1933	31.7	-0.4	-4.8	0.0	+2.0	+2.0	1.0	+2.0
		1932	30.6	+0.6	+0.4	+2.4	-2.4	0.0	1.0	0.0
		1937	26.1	-1.7	-0.2	-1.2	-0.2	-1.4	1.0	-1.4
								May-June		
2	15-25	1938	24.6	-0.4	+0.8	+1.6	+2.8	+2.4	0.66	+1.6
		1935	21.7	-1.0	0.0	+0.6	-0.8	+0.6	0.66	+0.4
		1936	20.2	+4.8	+4.2	+1.6	+0.8	+5.8	0.66	+3.8
		1939	19.9	+4.8	+3.3	-2.6	+2.0	+0.7	0.66	+0.5
		1928	17.6	-2.1	+5.8	-2.2	+1.0	+3.6	0.66	+2.4
		1929	16.8	-3.8	+1.1	-0.7	+1.2	+0.4	0.66	+0.3
								April-May		
3	5-15	1942	11.8	+0.8	-2.5	-5.0	-0.2	-1.7	0.33	-0.6
		1930	11.0	+5.0	-2.0	-1.8	+0.2	+3.0	0.33	+1.0
		1940	8.7	+0.7	+2.2	+0.4	-1.9	+2.9	0.33	+1.0
		1934	8.5	+8.4	+5.0	-1.0	+0.2	+13.4	0.33	+4.4
		1931	7.8	+1.6	+5.4	-0.8	+2.6	+7.0	0.33	+2.3
		1941	7.5	+0.2	+0.3	-3.4	+0.2	+0.5	0.33	+0.2

No.	Adj. water-content snow Apr. 1	April-Sep. dis-charge	Uncor-rected Apr.-Sep. forecast	Obtained as per cent of forecast	Devia-tion from 100	Adj. Apr.-Sep. forecast	Obtained as per cent of forecast	Devia-tion from 100
	in	ac-ft	ac-ft	pct	pct	ac-ft	pct	pct
1	33.7	56,850	55,200	103.0	3.0	56,800	100.1	0.1
	30.6	49,990	54,200	92.2	7.8	53,650	93.2	6.8
	24.7	44,920	49,600	90.6	9.4	47,400	94.8	5.2
2	26.2	51,792	48,100	107.7	7.7	49,100	105.5	5.5
	22.1	46,838	45,000	104.1	4.1	44,900	104.3	4.3
	24.0	50,668	43,550	116.3	16.3	46,900	108.0	8.0
	20.4	37,867	43,250	87.6	12.4	43,000	88.1	11.9
	20.0	48,110	41,000	117.3	17.3	42,600	112.9	12.9
	17.1	38,620	40,150	96.2	3.8	39,600	97.5	2.5
3	11.2	33,330	35,100	95.0	5.0	33,400	99.8	0.2
	12.0	32,306	34,300	94.2	5.8	34,250	94.3	5.7
	9.7	34,660	32,100	108.0	8.0	32,000	108.3	8.3
	12.9	35,131	31,750	110.6	10.6	35,200	99.8	0.2
	10.1	32,172	31,100	103.4	3.4	32,400	99.3	0.7
	7.7	31,970	30,750	104.0	4.0	30,000	106.6	6.6
			Mean	....	7.9	.....	....	5.3

[a] At Three Creeks Meadows Course. [b] For application to temperature-departure. [c] For application to water-content of snow on April 1.

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DISCUSSION

FRED H. PAGET (Division of Water Resources, California Department of Public Works, Sacramento, California)--Why neglect the temperature-effect during April and May of a heavy snow-year? The reason seems clear for not considering the temperature-effect during June and July of a dry year when the snow might all be melted by June, but it seems to me if one accepts the thesis that temperature-abnormalities affect the snow-pack during April and May of a dry year with little snowfall, it would have to follow that temperature-abnormalities during April to May of heavy snow-years should be considered. In such years there is an even greater snow-pack during April to May to be affected by temperature-abnormalities.

R. A. WORK--Mr. Paget's point has been considered in developing this correction. Temperature-correction was not applied for April to May in years of group (1) for the reason that approximately three-fourths of the total runoff for April to July occurred during June to July. Because of the very much greater runoff during June to July in years of heavy snowfall, the total temperature-correction was credited to those months.

If temperature-abnormalities during April to May are also to be considered in years of group (1), the month-groups should probably be weighted in proportion to their relative contributions to total runoff for the four-month period. On this basis June to July would be weighted 0.73 and April to May 0.27. Multiplying temperature-departure for June to July and April to May by these coefficients and adding the products, results in temperature-departures for April to July which slightly alter the ultimate correction-value as given in Tables 2 and 3.

Following this line of reasoning into group (2), April should be weighted 0.16 and May to June 0.84. As with group (1) years, application of the temperature-correction on this weighted basis slightly alters the ultimate correction-value as given in Tables 2 and 3. There is shown in the following tabulation, for both Squaw Creek and Tumalo Creek, the average deviation from 100, for 15 years, of the uncorrected correlation and the correlation corrected for temperature-abnormalities by the method described in this paper and for the additional months suggested by Mr. Paget.

Average deviation from 100 for 15 years

Stream	Uncorrected correlation	Correlation corrected for temperature-abnormalities in two months of average greatest runoff	Correlation corrected for temperature-abnormalities in April to July of group (1) years and April to June of group (2) years
Squaw Creek	8.2	5.3	5.7
Tumalo Creek	7.9	5.3	5.8

HARRY OLSEN (California Oregon Power Company, Medford, Oregon)--The foregoing paper constitutes a definite contribution to the art of forecasting spring and summer runoff from snow-measurements. The author is to be commended for the manner in which the matter has been presented. A vast amount of study and work must have gone into this paper.

As stated by the author, the purpose of the paper is to describe a method of adjusting snow-survey results of April 1 when constructing the forecast-curve so as to compensate for temperature-deviations from normal during the runoff-season [Factor (G)]. In the cases illustrated the corrections have been applied to previous years of record, resulting in a clear improvement over the uncorrected forecast-curves. A total of eight correction-factors, (A) through (H), are listed, the study being only concerned with the temperature-factor (G), and although probably outside the intended scope of the paper, we cannot help but wonder what the results would have been had the corrections been made, so far as possible, for all of the factors (A) through (H).

In comparing Tables 1 and 2, it is noted that the seasonal deviations from 100 are not parallel for the two watersheds under consideration even though the same snow-course measurements and temperature-departures are used. Although the watersheds are adjacent, it appears that some other factors than temperature have a marked effect on runoff. The Squaw Creek Watershed has a lower percentage of area below 6000 feet and a correspondingly greater percentage above than the Tumalo Creek Watershed. The fact that at present the results from but one snow-course are available may explain some of the large deviation of 17.6 for the year 1931 in the case of Squaw Creek as against only 0.7 for Tumalo Creek.

Figure 2, illustrating runoff of some adjoining streams, shows instances where the trend for a certain stream is not consistent with that of others. Unless there is an inaccuracy in the stream-flow records, then some other factor must have a marked effect upon runoff. As a matter of interest, the North Fork of Rogue River and Upper Klamath Lake, also in the Cascades, but of relatively larger drainage-areas, followed the pattern of Tumalo Creek in 1930 and 1931 as against the trends of Squaw Creek, Lake Creek, and McKenzie River. Had Squaw Creek followed the trend of Tumalo Creek the large deviation of 17.6 would have been far less. The stream-flow record at Squaw Creek for 1930 is shown in the Water-Supply Paper as fair to poor, and that for Lake Creek is shown as poor, so it may be that Factor (A), incorrect stream-discharge record, may have some effect in this case.

Assuming that factors (A) and (B) are the least responsible for the deviations, then factors (C) through (H) would have to be considered. Therefore, as before mentioned, although probably not within the scope of this excellent paper, I would certainly like to have the author discuss the probable effect of the several factors listed.

RAY K. LINSLEY, JR. (U. S Weather Bureau, Sacramento 9, California)--Mr. Work presents in Figure 3 a plotting of precipitation during December to March at Bend against runoff for April to September on Tumalo and Squaw creeks. From the poor relation evident he concludes that the use of precipitation-records at Bend for correcting for the effect of spring precipitation on runoff would be futile. Figure 3 is deceptive for two reasons as the attached Figure 1 indicates. First, Figure 3 is plotted on coordinates without the origin shown. Because of a relatively small variation in runoff, visual inspection indicates a much greater variation than actually is present. When an average line is sketched through the chart for Squaw Creek and the deviations are tabulated, the average deviation appears to be about 9,000 acre-feet or 19 per cent of the average runoff of 47,000 acre-feet. The maximum deviation occurred in 1930 with a deviation of about 24,000 acre-feet or 63 per cent.

The most misleading thing about Figure 3 is the fact that the rainfall is not plotted against the runoff it actually caused. Runoff of April to September represents a variable proportion of the total runoff resulting from any precipitation during December to March. In Figure 1 the runoff-period has been taken as November through September, while precipitation from November to March is used. It is believed that these periods give more comparable data. The average deviation in Figure 1 is 7,000 acre-feet or about 11 per cent of the average runoff of 62,000 acre-feet. The maximum deviation occurs in 1930 and 1940 of about 26 per cent. Although not reproduced here, a similar plotting was made using precipitation for November through June. The average error was found to be about ten per cent while the maximum deviation decreased to 20 per cent. It can be concluded, therefore, that a definite correlation between precipitation at Bend and runoff at Squaw Creek does exist. Presumably a similar correlation exists for Tumalo Creek. If the data used to plot Figure 1 were subjected to a thorough statistical analysis such as presented by LIGHT and KOHLER [Forecasting seasonal runoff by statistical methods, Trans. Amer. Geophys. Union, Part III, 1943], a satisfactory correlation would probably be found.

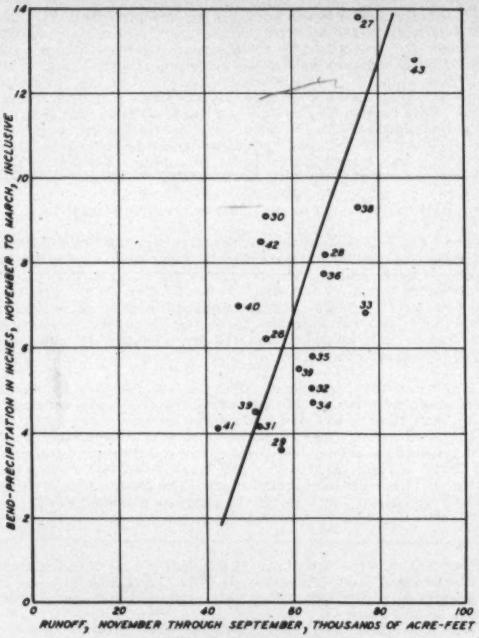

Fig. 1--Winter precipitation at Bend versus resulting runoff in Squaw Creek

GARFIELD STUBBLEFIELD (Engineer, Bureau of Reclamation, Sacramento, California)--It is suggested that determination of the area of snow-cover at intervals during the melting period should materially aid in correcting estimates of probable runoff, and should be helpful in flood-control operation of reservoirs.

Aerial photographs on a scale of about one-half inch per mile, similar to that used for the mapping of large areas of the European war-zones, should eventually provide an economically feasible method of delineating the major boundaries of the snow-pack.

MIDWINTER FORECASTING OF THE SNOW-WATER RUNOFF ON YEARS OF EXTREMELY LIGHT OR HEAVY FEBRUARY 1 MOUNTAIN SNOW-COVERS

Wayne D. Criddle and James C. Marr

Midwinter forecasts--The purpose of snow-surveys is to estimate the probable stream-flow from the mountain snow-pack prior to the beginning of the spring runoff and before final plans must be made for the summer by the various water-users.

In general, forecasting of stream-flow throughout the Columbia Basin and Intermountain States is done after receiving the results from the snow-surveys of April 1. A release of the survey-results and stream-flow estimates is made on or about April 10 by the Division of Irrigation, Soil Conservation Service, through the press, over the air, and by special bulletins. This date is usually sufficiently early to meet most needs, especially during the years of average or near-average runoff, that is, 25 per cent or more above or below normal. However, in case of extreme variations from average, the sooner the situation is known the better.

During years of flood-flow all of the time available between flood-warnings and its actual occurrence is generally needed for preparation against possible damage to reservoirs, bridges, and adjacent roads and lands. Likewise, early warning of drought gives farmers time to purchase desirable seed and properly prepare the land for a dry year. Power-companies are able to utilize the available water to the fullest extent and to plan to use other sources of power as may be required. It is during these unusual years that snow-surveying is of greatest importance.

In an attempt to determine the feasibility of making an earlier forecast during these unusual years, numerous past records were examined and curves plotted showing the variation of snow-water depth with time throughout the snow-accumulating months. Also, average records of precipitation of the United States Weather Bureau were studied to determine if the rate of accumulation of precipitation on the valley-floors during the winter months is similar to that of snow-pack in the higher areas.

Basis--After inspecting the records, some 39 snow-courses, scattered throughout the Columbia Basin in United States and Canada and on which measurements are made at least February 1 and April 1, were chosen for study. Only courses of higher elevation where it was believed little or no melting took place during the winter and early spring months were used. Most of the records for these courses extend back seven or eight years.

As a check on the results, average records for the past 26 years for eight courses on Snake River Watershed above Jackson Lake in Wyoming were analyzed. Also, individual records for the Lewis Lake Divide Snow-Course of this group were reviewed. Snow-survey records from the Mt. Logan Snow-Course located on Logan River Drainage, Utah, were examined for the period 1925 to date. Data from three courses in the Harney Lake and Umpqua River areas, Oregon, surveyed since 1927, were studied.

Data--Data for the snow-survey courses studied are shown in Tables 1 to 5. Table 1 contains data on the 39 courses from the Columbia Basin. It contains the name of the course, State, elevation, years of record, average annual maximum snow-water depth, per cent of average maximum for each month, and maximum and minimum increase of snow-water depth after February 1 for each course and the year it occurred.

Table 1--Average maximum snow-water depths and per cent of average snow-water depth on ground at first of each month for 39 courses in Columbia Basin, and maximum and minimum increase in snow-water depth after February 1

Snow-Course	State	Elevation	Years of record	Av. max. snow-water depth[a]	Maximum snow-water depth on ground at first of month					Average increase in snow-water after February 1			
					Jan.	Feb.	Mar.	Apr.	May	Year	Max.	Year	Min.
		ft		in	pct	pct	pct	pct	pct		in		in
Upper Columbia													
Farron	B.C.	4000	4	9.4	..	71	100	76	..	1940	5.0	1941	1.2
Glacier	B.C.	4100	4	18.0	..	71	77	100	..	1943	7.7	1941	3.4
	Watershed averages			13.7		71	88	88					
Kootenai River													
Red Mountain	Mont.	6000	5	16.1	..	73	90	100	68	1940	7.6	1941	1.1
Clark Fork River													
Benton Spring	Idaho	4900	7	17.5	40	70	95	100	54	1938	11.0	1941	0.0
Chessman Res.	Mont.	6200	7	4.4	41	68	100	98	20	1937	3.8	1941	0.0
Gibbons Pass	Mont.	7100	5	20.4	..	66	93	100	..	1940	9.1	1941	3.7
Lookout Pass	Idaho	5200	7	28.4	..	67	92	100	57	1937	14.6	1941	2.7
Marias Pass	Mont.	5250	7	14.8	48	68	93	100	40	1937	6.8	1941	0.0
Nesperce Pass	Idaho	6575	6	14.9	..	66	91	100	41	1943	7.4	1941	1.7
Pipestone Pass	Mont.	7200	5	5.0	..	58	76	100	35	1939	4.2	1941	1.4
Tenmile Cr.Upper	Mont.	8000	7	12.2	48	62	84	100	76	1937	7.4	1941	1.8
	Watershed averages			14.7	44	66	90	100	48	...	...	...	...
Okanogan River													
McCulloch	B.C.	4200	4	5.0	..	81	100	92	..	1940	1.9	1941	0.0
Trout Creek	B.C.	4700	4	4.4	..	70	89	100	..	1943	2.4	1941	0.8
	Watershed averages			4.7		76	94	96	..	...	...	...	...
Yakima River													
Cayuse Pass	Wash.	5300	3	64.5	46	68	86	100	102	1943	35.3	1941	6.6
Corral Pass	Wash.	6000	4	29.6	52	68	88	100	95	1943	16.6	1941	2.1
	Watershed averages			47.0	49	68	87	100	100	...	...	...	...
Upper Snake River Basin													
Aster Creek[b]	Wyo.	7700	25	29.3	49	74	91	100	..	1943	16.5	1941	1.1
Coulter Creek[b]	Wyo.	7600	25	20.6	55	82	99	100	..	1938	9.1	1941	1.9
Lewis Lake Div.[b]	Wyo.	7900	25	42.0	49	73	90	100	..	1936	20.8	1941	1.7
Blackrock	Wyo.	8600	8	20.7	..	64	..	100	..	1936	13.0	1942	4.9
CCC Camp	Wyo.	7500	8	11.9	37	62	88	100	..	1936	12.0	1941	1.6
Teton Pass	Wyo.	8500	5	25.5	30	57	85	100	..	1943	19.6	1941	6.6
Togwotee Pass	Wyo.	9600	8	26.6	..	66	..	100	..	1936	13.7	1942	6.8
	Watershed averages			21.3	33	62	86	100	..	...	...	...	...
Southern Tributaries--Snake River													
White Knob	Idaho	7700	8	10.2	30	49	85	100	..	1938	17.3	1941	2.1
Cape Horn	Idaho	6500	7	16.3	53	79	93	100	60	1937	8.8	1942	0.4
	Watershed averages			13.2	42	64	89	100	60	....	...	...	...
Blue Mtn.Springs	Ore.	5900	8	15.9	36	67	100	96	..	1938	14.4	1943	0.0
Anthony Lake	Ore.	7125	5	25.7	43	63	84	100	..	1939	16.4	1941	4.4
Aneroid Lake	Ore.	7480	2	30.0	..	74	..	100	..	1938	26.3	1941	9.1
	Watershed averages			23.9	40	68	92	99	..	...	...	...	...
Umatilla River													
Meacham	Ore.	5300	7	9.3	..	58	100	82	..	1939	9.3	1941	0.0
Toll Gate	Ore.	5070	8	25.4	..	61	..	100	..	1939	20.5	1941	1.5
	Watershed averages			17.4	..	60	100	91	..	...	...	...	...
John Day River													
Izee Summit	Ore.	5293	8	8.7	28	68	100	77	..	1938	7.1	1943	0.0
Olive Lake	Ore.	6000	8	17.2	32	58	90	100	..	1938	10.9	1941	3.9
Tipton	Ore.	5100	6	9.1	..	76	..	100	..	1938	5.4	1939	0.0
	Watershed averages			11.7	30	67	95	92	..	...	...	...	...
Deschutes River													
Cascade Summit	Ore.	4880	7	26.9	..	63	..	100	61	1938	22.6	1941	0.0
Derr	Ore.	5670	6	9.0	..	64	..	100	..	1938	10.2	1941	0.0
Ochoco Meadows	Ore.	5200	6	11.2	..	71	100	91	..	1937	8.9	1936	0.0
	Watershed averages			15.7	..	66	100	97	61	...	...	...	...
Willamette River													
Hogg Pass	Ore.	4755	6	35.6	..	59	..	100	..	1938	29.0	1941	4.2
Phlox Point	Ore.	5600	6	51.4	29	58	86	100	..	1938	33.9	1941	2.6
	Watershed averages			43.5	29	58	86	100	..	...	...	...	...
White River													
Sun Top Mtn.	Wash.	4900	2	19.2	58	66	97	100	..	1943	8.6	1941	0.1
White River Ent.	Wash.	3600	3	12.7	..	70	100	..	..	1943	7.7	1941	0.0
	Watershed averages			16.0	58	68	98	100	..	...	...	...	...
Grand total	....	....	..	775.0	804	2609	2842	3712	709	...	502.8	...	79.0
No. of items	....	....	..	39	19	39	31	38	12	...	39	...	39
Averages	....	....	..	19.9	42	67	92	98	59	...	12.9	...	2.0

[a] Either March 1 or April 1, depending on which is greater. [b] Measurements made approximately the middle of the month instead of the first.

Tables 2 to 5 show the average monthly snow-water depth and per cent each is of the average maximum during the period of record for the Wyoming, Oregon, and Utah courses. These data are shown graphically in Figures 1 to 5.

Table 2--Average snow-water depths and per cent each is of average maximum (22.5 inches) for eight courses on Upper Snake River above Jackson Lake, Wyoming, at approximately the middle of each month, 1919 to 1943

Year	January		February		March		April	
	Average	Pct av. max.	Average	Pct av. max.	Average	Pct av. max.	Average	Pct av. max.
	in	pct	in	pct	in	pct	in	pct
1919	8.3	37	12.4	55	17.3	77	19.1	85
1920	9.9	44	14.2	63	22.1	98	23.5	104
1921	. . .	. .	18.2	81	21.2	94	23.0	102
1922	14.6	65	18.6	83	22.5	100	24.4	108
1923	11.7	52	16.1	72	21.3	95	23.7	105
1924	11.2	50	14.1	63	16.6	74	18.7	83
1925	13.2	59	24.8	110	26.8	119	23.0	102
1926	8.0	36	14.4	64	17.1	76	16.4	73
1927	19.0	84	28.0	124	34.2	152	37.2	165
1928	19.0	84	21.4	95	24.5	109	32.8	146
1929	9.1	40	17.0	76	20.9	93	22.2	99
1930	8.5	38	13.9	62	17.3	77	12.1	54
1931	5.3	24	6.3	28	8.6	38	9.3	41
1932	12.1	54	20.2	90	24.4	108	25.8	115
1933	10.9	48	19.4	86	22.2	99	24.7	110
1934	8.9	40	13.1	58	15.4	68	16.2	72
1935	12.6	56	14.8	66	18.4	82	24.4	108
1936	14.2	63	23.7	104	30.6	136	32.8	146
1937	8.7	39	16.5	73	20.3	90	24.9	111
1938	11.8	52	19.4	86	23.1	103	28.3	126
1939	11.9	53	21.1	94	24.6	109	19.5	87
1940	6.4	28	11.5	51	18.9	84	18.4	82
1941	11.5	51	15.5	69	16.1	72	13.7	61
1942	9.8	44	14.8	66	17.1	76	14.2	63
1943	23.8	106	34.2	152	38.2	170	33.8	150
Average	11.7	52	17.7	79	21.4	95	22.5	100

Results--For the years of record at all courses, except the three Oregon courses during 1938, it was found that during years of extremely light snowfall the snow-water depth on February 1 was consistently well below normal. Likewise for years of high snowfall and resulting high stream-flow, the snow-water depth on February 1 was consistently well above normal. These data indicate that this result may be expected in the interior Columbia River Basin. However, this same result may not hold true for the Pacific Coast areas which are influenced by Pacific storms, as is indicated by the three Oregon courses. Results from the Oregon courses show an unusually high increase in the snow-pack occurred after February 1 in 1938, changing from below normal on that date to the maximum of record.

The average maximum and minimum increase in snow-water depth after February 1 for the period of record and the year they occurred are shown in Table 6. It is interesting to note that during some years the increase after February 1 is practically negligible.

Table 3--Average snow-water depths and per cent each is of average maximum (42.0 inches) for Lewis Lake Divide Snow Course, Yellowstone National Park, at approximately the middle of each month, 1919 to 1943

Year	January		February		March		April	
	Average	Pct av. max.	Average	Pct av. max.	Average	Pct av. max.	Average	Pct av. max.
	in	pct	in	pct	in	pct	in	pct
1919	14.0	35	18.0	43	36.0	86	37.0	88
1920	16.5	39	24.0	57	37.5	89	39.0	93
1921	. . .	. .	27.0	64	36.0	86	49.0	117
1922	26.5	63	31.5	75	36.0	86	42.0	100
1923	20.0	48	28.5	68	35.0	83	43.0	102
1924	18.0	43	22.0	52	26.5	63	32.0	76
1925	24.0	57	46.0	110	48.5	115	47.5	113
1926	15.0	36	32.0	76	35.0	83	38.0	90
1927	40.0	95	60.0	143	72.0	171	76.0	181
1928	35.0	83	43.0	102	47.0	112	60.0	143
1929	15.0	36	26.0	62	33.0	79	36.0	86
1930	15.0	36	27.0	64	32.0	76	24.0	57
1931	6.5	15	8.5	20	13.0	31	17.0	40
1932	20.0	48	33.5	80	42.0	100	45.0	107
1933	16.0	38	34.0	81	36.0	86	41.5	99
1934	16.0	38	22.5	54	26.0	62	35.5	85
1935	22.0	52	24.5	58	33.0	79	44.0	105
1936	25.4	60	38.5	92	51.0	121	55.0	131
1937	15.0	36	25.0	60	33.5	80	43.0	102
1938	21.2	50	35.4	84	40.5	96	52.5	125
1939	21.0	50	35.1	84	44.2	105	36.5	87
1940	9.9	24	16.4	39	30.1	72	37.2	89
1941	19.2	46	26.8	64	28.5	68	27.6	66
1942	16.7	40	25.4	60	28.6	68	28.5	68
1943	42.0	100	55.4	132	62.6	149	62.5	149
Average	20.4	49	30.6	73	37.7	90	42.0	100

Table 4--Average snow-water depths and per cent each is of average maximum for Mt. Logan Snow-Course, Logan River, Utah, at approximately the first of each month, 1924 to 1938

Year	January		February		March		April		May	
	Average	Pct av. max.	Average	Pct av. max.	Average	Pct av. max.	Average	Pct av. max.	Average	Pct av. max.
	in	pct	in	pct	in	pct	in	pct	in	pct
1924	. . .	. .	. . .	. . .	. . .	. .	25.8	88	21.2	72
1925	14.6	50	19.5	67	24.9	85	32.1	118	28.3	97
1926	5.4	18	10.9	37	18.0	61	21.9	75	. . .	. .
1927	12.9	44	20.8	71	34.5	. .	41.5	142	36.8	125
1928	17.3	59	22.4	77	23.1	79	31.2	106	27.3	93
1929	11.0	38	21.2	72	28.1	96	35.0	119	37.0	126
1930	5.0	17	15.0	51	22.7	77	28.5	97	18.3	62
1931	6.1	21	8.8	30	11.1	38	13.4	46	14.2	48
1932	12.7	43	20.1	69	32.6	. .	42.3	144	44.1	151
1933	8.8	30	15.5	53	25.0	85	28.4	97	29.0	99
1934	7.1	24	10.2	35	12.7	43	18.2	62	. . .	. .
1935	11.9	41	18.5	63	20.1	69	27.9	95	30.9	105
1936	7.5	26	20.9	71	34.6	. .	38.3	130	37.8	129
1937	8.2	28	13.4	46	22.2	76	27.4	94	. . .	. .
1938	8.7	30	. . .	. .	. . .	. .	27.5	94	15.1	52
Average	9.8	33	16.7	57	23.8	81	29.3	100	28.3	97

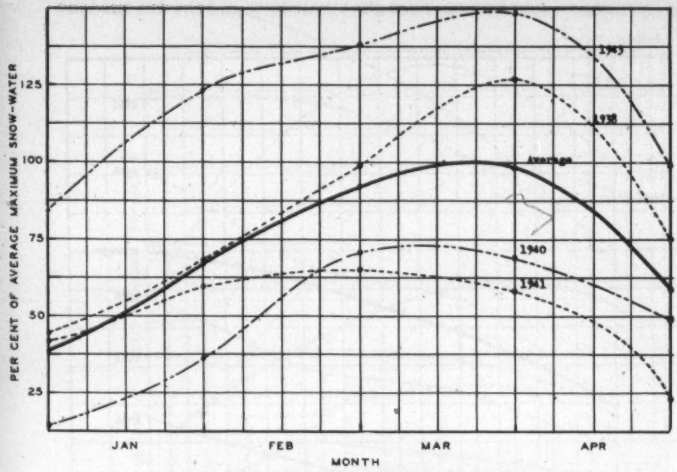

Fig. 1--Variation of snow-water depth in per cent of average maximum for 39 stations throughout Columbia Basin

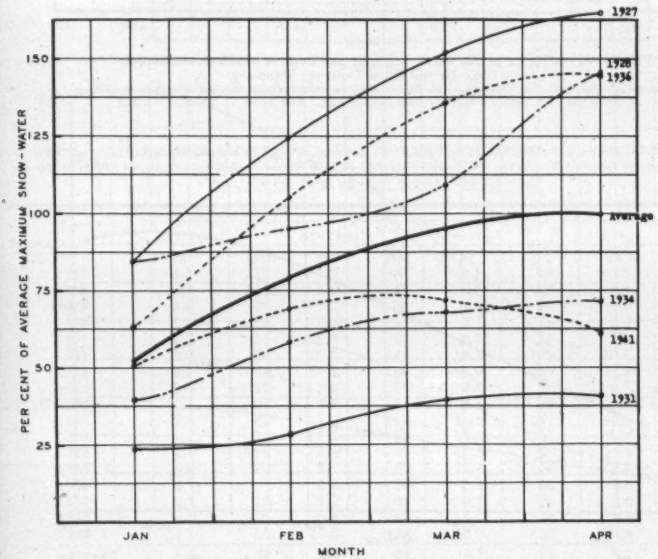

Fig. 2--Variation of snow-water depth in per cent of average maximum for 8 snow-courses above Jackson Lake, Snake River, Idaho

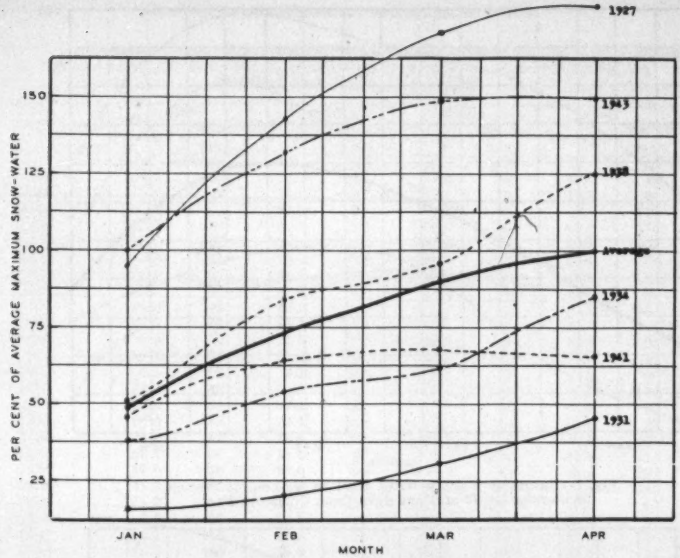

Fig. 3--Variation of snow-water depth in per cent of average maximum, Lewis Lake Divide Snow-Course, Wyoming

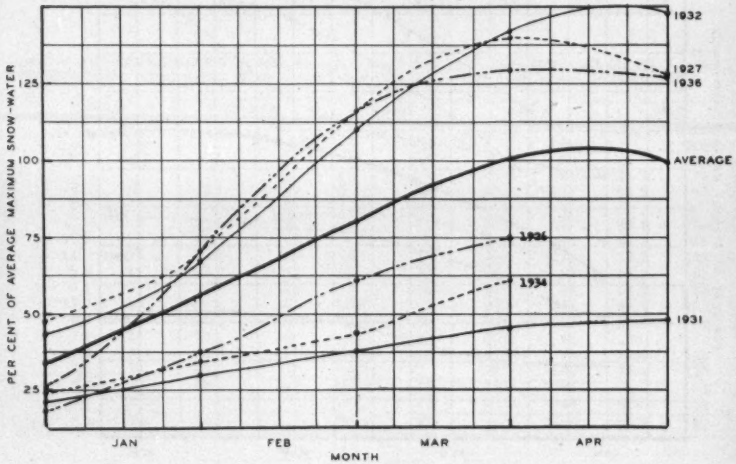

Fig. 4--Variation of snow-water depth in per cent of average maximum, Mt. Logan Snow-Course, Utah

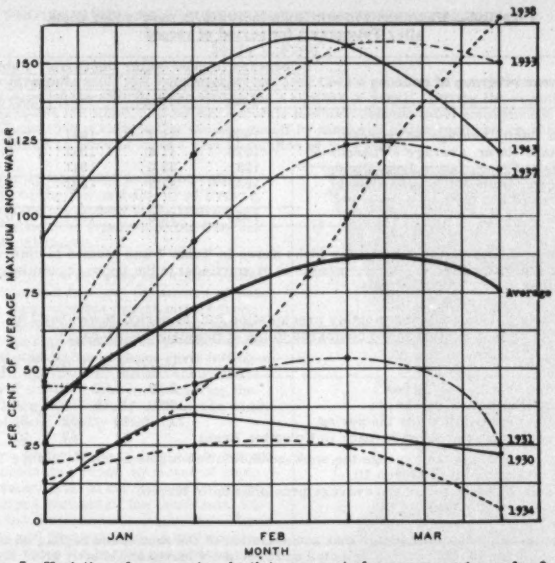

Fig. 5--Variation of snow-water depth in per cent of average maximum for 3 snow-courses in Klamath Lake Basin and Umpqua River Areas, Oregon

Table 5--Average snow-water depths and per cent each is of average maximum (11.9 inches) for three courses in Klamath Lake Basin and Umpqua River Areas of Oregon on approximately the first of each month, 1927 to 1943

Year	January		February		March		April	
	Average	Pct av. max.	Average	Pct av. max.	Average	Pct av. max.	Average	Pct av. max.
	in	pct	in	pct	in	pct	in	pct
1927	5.8	49	6.6	55	9.3	78	11.5	97
1928	5.7	48	5.0	42	5.7	48	6.3	53
1929	3.8	32	7.2	80	7.4	62	5.6	47
1930	1.1	9	4.2	35	3.4	29	2.6	22
1931	5.2	44	5.4	45	6.3	53	3.0	25
1932	7.6	64	16.2	136	12.1	102	12.8	107
1933	5.5	46	14.3	120	18.6	156	17.9	150
1934	1.6	13	3.0	25	2.8	24	0.5	4
1935	7.3	61	8.5	71	9.4	79	9.2	77
1936	5.0	42	14.0	118	15.6	131	12.6	106
1937	3.1	26	10.9	92	14.6	123	13.7	115
1938	2.3	19	5.0	42	11.8	99	19.6	165
1939	2.8	24	7.1	60	12.4	104	10.9	92
1940	0.3	3	2.3	19	5.7	48	5.4	45
1941	2.3	19	7.6	64	9.1	76	3.0	25
1942	4.2	35	5.1	43	10.2	86	6.4	54
1943	11.1	93	17.3	145	18.6	156	14.4	121
Average	4.4	37	8.2	69	10.2	86	9.1	76

Table 6--Maximum and minimum increase in snow-water depth after February 1 for period of record

Course or group of courses	Increase in snow-water depth after February 1			
	Maximum		Minimum	
	Year	Increase	Year	Increase
		in		in
Columbia Basin, average 39 courses	1938	11.7	1941	2.0
Upper Snake River, average 8 courses	1928	11.4	1941	0.6
Upper Snake River, Lewis Lake Divide	1921	22.0	1941	1.9
Logan River, Utah, Mt. Logan Course	1932	22.2	1931	4.6
Klamath Lake and Umpqua River, Oregon, average 3 courses	1938	15.0	1934	0.3

The average monthly precipitation for Idaho shown in Table 7 was studied to determine if the rate of accumulation through the winter months is proportional to the snow-accumulation at the higher elevations.

Table 7--Accumulated monthly precipitation for the period November 1 to March 20 in Idaho compared to the accumulated snow-pack[a]

Item	Nov.	Dec.	Jan.	Feb.	Mar.[b]
Average Idaho precipitation, inches[c]	2.08	2.07	2.16	1.76	1.18
Accumulated precipitation, inches	2.08	4.15	6.31	8.07	9.25
Per cent of total precipitation for the period	22	45	68	87	100
Per cent of average maximum snow-pack in Columbia Basin	...	42	67	92	98

[a] It is assumed that on an average the snow-accumulation begins about November 1 and reaches a maximum about March 20.

[b] Includes only two-thirds of the average precipitation in March.

[c] For period 1894 to 1943.

The snow-survey records indicate that accumulation of the snow-pack begins, on an average, about November 1 for the 39 courses selected and reaches a maximum shortly after the middle of March. Therefore, the accumulation of the Idaho precipitation for purposes of comparison was begun on that date and only two-thirds of the precipitation during March are included. It is interesting to note the close agreement of the percentages of snow-pack with that of the precipitation. After January or on February 1, 68 per cent of the precipitation for the period has occurred, whereas 67 per cent of the snow-pack is down.

Summary and conclusions--(1) During recent years an unusually light or heavy snow-pack in the interior of Columbia River Basin on February 1 has been the forerunner of a light or heavy total snow-pack at end of winter and the resulting runoff from the melting snow has been extremely small.

(2) For unusual water-years in Columbia Basin, forecasts should be made on February 1 definitely telling the people to expect a high or low runoff-year.

(3) Because of the large benefits which can accrue from early forecasts during years of unusual runoff, the risks involved from making these early forecasts appear justified.

(4) The periods of record for interior Columbia River Basin snow-surveys are not sufficiently long to establish with certainty the correctness of forecast-possibilities for February 1, but there is complete agreement as to these records with respect to the forecast for February 1. Courses in Utah, Wyoming, and Oregon with longer records further substantiate this theory.

(5) No well-defined cycle-tendency in maximum snow-pack is noticeable. It is not unusual to find the year of highest maximum snow-pack on record preceded by the lowest, or vice versa.

(6) February snow-packs within 25 per cent of the normal on February 1 may have no significance and no special emphasis should be placed on them.

(7) If the forecast for February 1 should be in error due to changing conditions subsequent to that date, the reason for issuing such early forecast no longer exists, and forecasts for March 1 or April 1 will be timely as during ordinary years.

U. S. Department of Agriculture, Soil Conservation Service,
Boise, Idaho

A PHOTOGRAPHIC SNOW-SURVEY METHOD OF FORECASTING RUNOFF

Harry L. Potts

The forecasting of runoff and water-supply has long been a problem of general interest and has intermittently engaged the efforts of the writer for a number of years. During the recent period of drought the necessity for more reliable and accurate methods became most emphatically apparent. It is on the possibilities of forecasting stream-runoff by means of photographs which will be submitted in this paper as being at least a partial solution of the problem.

Being directly interested in the domestic water-situation of the City and County of Denver, the writer confined his studies to the headwaters of the South Platte River from which the City derives its principal supply.

In approaching the problem the writer recognizes the fundamental fact that the amount of water flowing in the local streams comes mainly from two sources: (1) The melting snow which has accumulated on the high mountain ranges during the winter months; and (2) the summer rains falling on the watershed. It, therefore, seems desirable to consider both of these factors in forecasting the runoff of a stream, particularly in Colorado where it seems to be about equally divided.

In 1930 the writer began to investigate the possibilities of forecasting runoff by means of photographing the snow-fields at the headwaters of the streams. Various sections of the Continental Divide near the headwaters of the South Platte River were observed and photographed, as well as certain sections of the lower ranges and divides where heavy snowdrifts were to be found in the early months of the year. Due to the fact that the snow at the lower altitudes had almost entirely disappeared before the runoff-peak had been reached, it became apparent that the higher elevations would have to be relied upon for the desired data.

Being entirely "upon his own" and limited by time, funds, and opportunity, some four years were spent in preliminary studies and experiments. Various sizes and types of cameras and lenses were tried out before satisfactory results were obtained.

The actual collection of the basic data was begun in the spring of 1934 by photographing a section of the Continental Divide near Hoosier Pass at the headwaters of the Middle Fork of the South Platte River. This section of the range is high and rugged, and contains many small canyons and gulches which drift full of snow during the winter and early spring. These immense drifts seldom completely disappear during the summer months and it was for this reason that this particular spot was chosen as being a suitable index of stream-flow conditions.

An automatic recording station was installed a few miles downstream to measure the runoff from the area and a precipitation-gage established nearby.

Fig. 1--Typical panorama showing sectioning

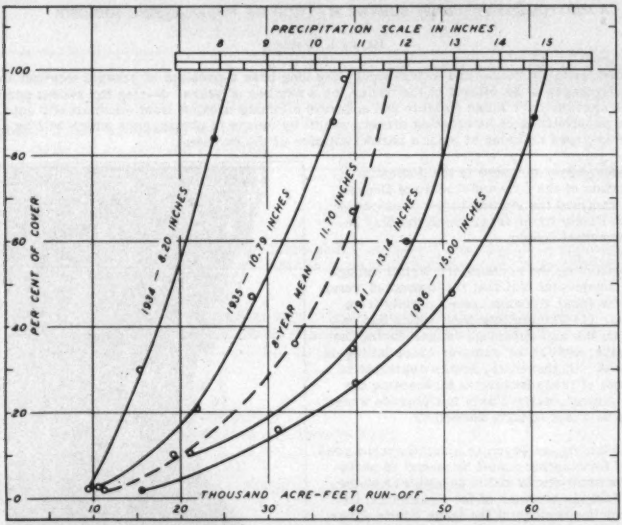

Fig. 2--Graphs of percentage-cover to runoff and precipitation-scale for 1934, 1935, 1936, 1941, and of 8-year mean

A series of photographs was taken of this section of the range at intervals throughout the year, and the per cent of the area covered by snow in each photograph was calculated and recorded, each photograph being taken from the same point on the hillside. The entire area covered by the photographs was not used in the actual calculations but was found to be beneficial as supporting data in many instances. The area observed, being arbitrarily chosen and extending for several miles along the divide, lies almost entirely above timber-line.

In determining the per cent of cover or the "coverage-factor" of the observed area, a transparent template of cross-section paper was superimposed on the photograph and the total number of small squares counted in which snow appeared, which, divided by the total number of small squares in the template, indicated the per cent of the observed area covered by snow. Each photograph taken was thus measured, the same identical area being observed in each case.

At the end of the season, or on November 1, when the streams at this altitude usually freeze up and make further measurement impractical, the total runoff was calculated from the date on which each photograph was taken to the end of the season on November 1.

A chart, shown in Figure 2, was prepared on which these data were plotted showing the coverage-factor and the measured runoff for each photograph. A runoff-curve was drawn in for the year on which was noted the recorded rainfall during the period of observation.

The records for the year of 1935 and 1936 were likewise plotted on the same chart with the result that three separate curves were obtained for the three individual years, each year showing considerable variation in precipitation.

If the theory is correct that runoff from snowfall may be forecast by means of the area-method as shown by photographs, the distance between the three individual curves should be approximately proportional to the differences in the recorded precipitation.

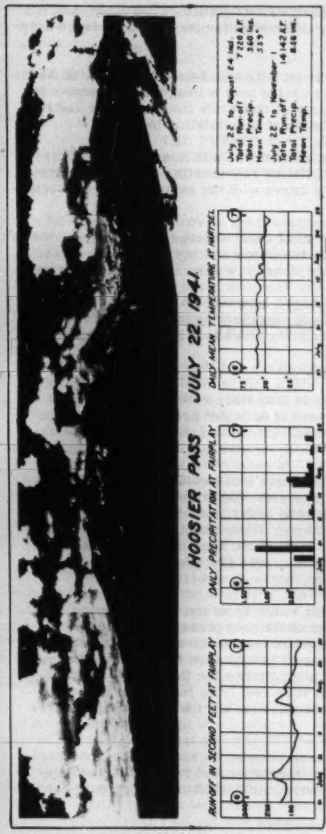
HOOSIER PASS JULY 22. 1941
RUNOFF IN SECOND FEET AT FAIRPLAY
DAILY PRECIPITATION AT FAIRPLAY
DAILY MEAN TEMPERATURE AT HARTSEL
July 22 to August 24 Inc.
Total Run-off 7200 A.F.
Total Precip. 1.65 in.
Mean Temp. 55°.
July 22 to November 1
Total Run-off 14142 A.F.
Total Precip. 8.46 in.
Mean Temp.

Fig. 3--Panorama of Hoosier Pass on July 22, 1941, and charts of runoff and precipitation at Fairplay and of daily mean temperature at Hartsel, July 21 to August 25, 1941

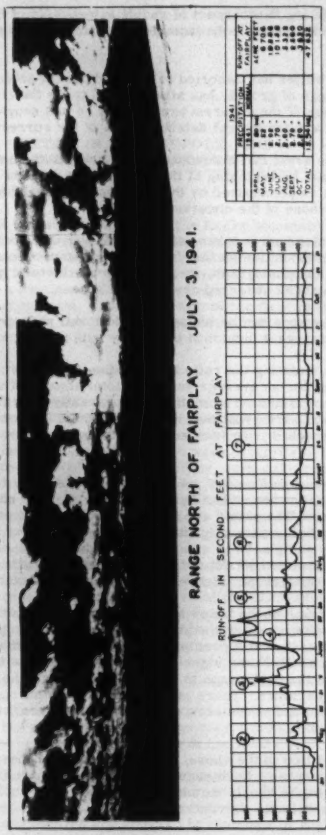

Fig. 4--Panorama of range north of Fairplay on July 22, 1941, and graph of runoff at Fairplay, April 30 to October 31, 1941

A scale was therefore laid out on the chart, as shown in Figure 2, connecting the curves representing the extreme years and being proportional to their difference in precipitation. This scale, being intersected by the middle year curve at almost exactly the point representing the recorded precipitation for that year, would seem to prove the correctness of the theory.

The investigations have been continued and we now have a record covering a period of ten years which seem to strengthen and support the theory. While it is true that certain years did not follow the pattern as closely as others, it was found upon investigation that this deviation was caused by some unusual condition. Heavy rains during the latter end of the season would tend to spoil the symmetry of the curve as well as a succession of light showers which were not heavy enough to affect the runoff but would increase the record of precipitation for the year. A mean of the ten years of record plotted on the original chart gives us a smooth symmetrical curve which falls into its proper position on the scale of precipitation.

In making the forecast of runoff an estimate of the anticipated rainfall must be made, and if a normal year seems to be indicated the curve representing an average for the years of record may be used.

The writer has resorted to the study of the trees in the vicinity and, by measurement of the annual rings of growth, has attempted to trace the climatic cycles over a long period of time. By observation of the apparent cycle-trend he has sought to project this cycle into the future and thus arrive at a more logical determination of the correct estimate of precipitation to use.

In the event that a deviation from normal seems to be indicated an additional curve is drawn on the chart by beginning at the point on the scale of precipitation representing the probable precipitation as determined by the observer and sketching in a curve with the same general characteristics as those of the observed years.

A photograph is taken, say about May 1, and the per cent of cover measured. Then from the point of intersection on the "normal-year curve" shown on the chart, and the per cent of cover shown by the photograph, we read directly the total quantity of water which can reasonably be expected from the observed area for the season.

At any time during the season additional photographs and observations may be made and an amended forecast furnished to comply with any unusual deviation which may have occurred.

By calculating the ratio between the total runoff from this area and the total diversion at the city-intake for an average year, the total amount of water which will be available for use by the city is determined. The method is apparently very flexible in that other ratios may be used as required, or, in the event that indications seem to denote a year of deficient precipitation, a curve may be sketched in for any amount of rainfall which, in the opinion of the forecaster, may be expected.

As mentioned before, each photograph is taken from the same location and usually consists of four separate views taken in such manner that the edge of one view slightly overlaps the next adjacent view. The prints are trimmed and mounted on a sheet of heavy linen-backed drawing paper cut to a suitable size, allowing for a wide margin at the bottom. These sheets are numbered consecutively and placed in a loose-leaf binder. A panoramic view of the area is thus obtained on which is tabulated all data relating to that particular photograph (see Fig. 3). In the wide margin below the photograph is shown three graphs and a tabulation.

The graph at the lower left-hand corner shows the daily runoff from the area in second-feet, from the date on which the photograph was taken to the date of the next photograph. The second graph shows the daily precipitation, and the third the daily mean temperature for the period. The tabulation at the lower right-hand corner shows the total runoff in acre-feet from the area from the date of the photograph to the date of the next, the total precipitation for the period, and the mean temperature. There is also shown the total runoff in acre-feet from the date of the photograph to the end of the season on November 1, the total precipitation, and the mean temperature for the season.

In addition to the above, the per cent of the observed area covered by snow or the "coverage-factor" is shown. Each page in the album thus presents an interesting and rather complete story. No photographs should be taken immediately after a fresh snow, although it may be permitted by applying a suitable correction.

At the end of the season an index-sheet is made up for the year (see Fig. 4) showing a graph of the daily runoff from about April 15 to November 1, the dates and page numbers of the several photographs, a comparison of the current and normal precipitation for the various months, and other pertinent data.

Additional years of record will undoubtedly add to the accuracy and value of this study. Certain changes in methods and equipment may be made from time to time as appear necessary, but it is our opinion that runoff from accumulated snows in certain areas may be forecast from photographs with more accuracy than has been attained in the past. The advantages of observing a relatively large area will, we believe, more than compensate for the various minor errors which are known to exist in this method.

An extension of the method to other watersheds would be desirable and beneficial, but it is beyond the power of an individual observer to cover a wide territory. It is the opinion of the writer

that the entire western area of the United States would be a fruitful field for further investigations in the development of the method and in some instances aerial photography would no doubt be desirable.

Board of Water Commissioners,
Denver, Colorado

THE EFFECT OF TIMBER CUTTING IN A LODGEPOLE-PINE FOREST ON THE STORAGE AND MELTING OF SNOW

H. G. Wilm

As a part of research on the management of forested watersheds, the Rocky Mountain Forest and Range Experiment Station has conducted intensive experiments in Colorado to find out how timber cutting in a lodgepole-pine forest influences the amount of water available for stream-flow [see 2 of "References" at end of paper]. Among the various factors involved in this influence, the storage and melting of snow obviously assumes a dominant role. Accordingly, an intensive series of measurements has been devoted to this factor; and now, with completion of the first phase of the investigations, definite information is available on how timber cutting in this forest-type influences the storage and melting of snow.

Organization of experiments

Most of our research in this field has been concentrated on a group of 20 five-acre plots, supporting a mature stand of lodgepole pine. On these plots intensive snow-measurements have been taken since 1938 by means of weekly surveys, starting about March 15 of each year and ending about June 1, with the disappearance of snow from all of the plots. Each week, records of snow-depth and water-content were taken at 25 locations on each plot. In addition, rain-gage records provided estimates of the amount of precipitation added to the snow during the melting period and to the wet soil thereafter, until such precipitation could no longer be expected to add water to the ground-water table--about June 30. (Records of precipitation were actually continued throughout the summer season [2]; but discussion of these is outside the scope of the present paper.)

The first two years of records were designed to show how much snow was stored in the uncut forest, how long the stored snow remained on the ground, and how storage and melting were affected by variations in the density of the forest canopy. Then, in 1940, 16 of the plots were cut-over to leave various reserve stands of merchantable timber. Four of the plots were left uncut, all trees larger than 9.5 inches in diameter were removed from four plots, and four each were left with merchantable reserve stands of 2000, 4000, and 6000 board-feet per acre. Even where the cutting was heaviest, an open stand of smaller trees remained to provide partial shade and to protect the soil.

After treatment, records were continued for three years, until conclusive information on the effects of timber cutting was procured. Since, however, these influences may change over a longer period of time, additional records will be obtained at ten-year intervals in the future.

In addition to the studies in mature lodgepole pine, similar measurements were taken in stands of young second-growth pine occupying areas which were cut-over and burned about 30 years ago. Again, the purpose of these records was to show how much snow was stored under this kind of forest-cover, and to find out how snow-storage and melting are affected by openings of various sizes in the forest-canopy.

Results

For the mature pine-forest, the results obtained from records of pretreatment have been published in an earlier paper [3]. Briefly, these data showed that initial snow-storage and duration of melting increased with the average distance of any sampling point from the surrounding crowns; the smallest quantities of snow were stored within dense clumps of trees, and the largest amounts in the largest available openings, about 60 feet in diameter.

After the treatments were applied, timber cutting exerted a strong influence on the amounts of water stored in snow before melting began in the spring and on the amount of precipitation added to the snow and soil between the first snow-survey and June 30 of each year. As shown in Table 1, an average of 9.59 inches of water was stored on the most heavily cut-over plots before melting

began, as compared to only 7.60 inches of water on the uncut plots. The average amount of added precipitation was 7.56 inches under the heaviest treatment, and only 5.73 inches on the uncut areas. This means that the forest on the uncut plots intercepted and evaporated 1.99 inches more precipitation than the heavily cut-over forest during the period of winter snow-accumulation, and 1.83 inches more water during the spring.

Table 1--Influence of timber cutting in mature lodgepole pine on snow-storage and net precipitation during the period of snow-melt

Factor	Merchantable reserve stand, bd-ft/ac				
	11,900 (uncut)	6000	4000	2000	0
	All data in inches of water				
Initial storage of snow	7.60	8.41	8.61	9.09	9.59
Precipitation added during snow-melting period	5.73	6.60	7.01	6.94	7.56
Total	13.33	15.01	15.62	16.03	17.15

When the factors of initial snow-storage and added precipitation are combined, we find that a total of 17.15 inches of water passed through the forest-canopy on the heavily cut-over plots, as compared to only 13.33 inches in the uncut forest; there was an excess due to timber cutting of 3.82 inches, or about 29 per cent. Intermediate effects were shown by the other three treatments in approximately linear relation to the reserved volume of merchantable timber. While obviously these figures are subject to sampling errors, the influence of the timber-cutting treatments was far greater than might have been expected by chance.

Probably because of greater exposure to Sun and wind, the snow on the cut-over areas melted more rapidly than on the uncut plots. These accelerated melting-rates were compensated, however, by the excess snow stored initially on the cut-over areas, so that at the end of each season all 20 plots became bare at practically the same time.

Although the results of our studies in second-growth lodgepole pine have been reported elsewhere [1], it seems worth while to review them for this discussion. These experiments showed that the amount of snow stored before melting began and the duration of melting are both strongly influenced by the size of openings in the crown-canopy of a dense stand of young lodgepole-pine. The smallest amounts were stored in the smallest openings, and the largest amounts in openings larger than 20 feet in diameter--about the height of surrounding trees. Still larger openings provided no further increases in snow-storage, and the additional exposure of the snow to Sun and wind induced more rapid melting. From these results we concluded that, in general, maximum initial snow-storage and optimum melting-rates should be afforded by openings which are about equal in diameter to the height of surrounding trees.

Conclusions

Experiments conducted in mature forests of lodgepole pine have shown that an unmanaged stand does not furnish optimum conditions for the storage of snow, and that these conditions can be substantially improved by carefully managed timber cutting. The object of such cutting should be to open the forest-canopy so as to minimize losses due to interception of snow and still to retain a forest dense enough to shade the ground and to protect the watershed against erosion.

In second-growth lodgepole pine, our findings indicate the desirability of thinning such stands for the purpose of improving water-yield as well as accelerating the growth of the remaining trees. This kind of thinning, designed to provide a maximum number of shaded openings, should amply justify its cost in many of the dense stands of second-growth lodgepole-pine which characterize large areas of watershed-land in the Rocky Mountains.

These results obviously apply only to areas where water-yield is of prime importance, and where floods and erosion present no real problem. In areas of more delicate physiographic balance, where any pronounced disturbance of the watershed-cover may result in serious damage, only the most conservative timber cutting may be permitted. And for maximum protection against floods the forest should be kept as dense as possible, so as to promote maximum consumption and storage of flood-producing precipitation. In many western watersheds, however, well-managed timber cutting should provide desirable conditions for snow-storage and water-yield, at the same time allowing an income from the sale of timber-products.

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[2] Rocky Mountain Forest and Range Experiment Station, Annual report for 1943, Mimeo. 46 pp., December, 1943.
[3] H. G. WILM--The influence of a lodgepole-pine forest on storage and melting of snow, Trans. Amer. Geophys. Union, Part II, pp. 505-508, 1940.

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THE USE OF SNOW-SURVEYS AS AN AID IN FLOOD-CONTROL OPERATION OF RESERVOIRS

Francis G. Christian

The writer's remarks will be confined to a discussion of the paper by FRED PAGET on "The use of snow-surveys as an aid in flood-control operation of reservoirs", presented at Corvallis, Oregon, on June 16, 1943, and published in the Transactions of 1943 of the American Geophysical Union. In that paper it was shown how the information revealed by snow-surveys may be applied to the problem of operation of reservoirs for the control of snow-melt floods and yet allow maximum conservation of water for purposes of irrigation and power. As stated by Mr. Paget, two possible extreme variations in the manner of the occurrence of runoff must be considered--early snow-melt and late snow-melt. One of these conditions makes flood-control the most difficult and the other makes the filling of the reservoir at the end of the season the most difficult. Flood-control requires that reservoir-space be provided to take care of runoff from early melting, while water-conservation requires that the reservoir be not kept so low that runoff from late melting would fail to fill it.

It will be recalled that Mr. Paget prepared two runoff-distribution graphs--one for early snow-melt runoff [see Fig. 5, p. 33, Part III, Trans. Amer. Geophys. Union, 1943], and the other for late snow-melt runoff [see Fig. 6 of reference above]. The graph for early snow-melt runoff showed for various quantities of runoff during April to July in a specific stream, (1) the earliest date when the flow in that stream could be expected to reduce to a quantity which would not cause flood-damage and (2) the maximum total amount of runoff that might occur from April 1 to that date. Similarly the graph for late snow-melt runoff showed (1) the latest date after which the flow should not be expected to exceed the demands for irrigation and (2) the maximum total amount of runoff that might occur from that date to July 31.

It will also be recalled that Mr. Paget prepared a graph--designated a thermo-hydrograph--showing daily maximum temperatures and daily river-discharges [see Fig. 3, p. 31, of reference above]. It was pointed out that an examination of the thermo-hydrograph indicates that, despite daily variations, the trend of temperatures is upwards as the season advances; that this is also true of runoff until the time when the snow-pack is so depleted that increased temperature cannot melt more snow each day; and that after this maximum point the general trend of runoff is downward. During any given year the chart would be plotted each day with the view of possibly foreseeing the daily peaks several days in advance and of recognizing the start of the decline in runoff in ample time to insure that water needed for storage be not wasted needlessly.

Taking into account the fact that actual runoff may depart ten per cent from the forecast, Mr. Paget suggested the following operation criteria for the proposed Pine Flat Reservoir on Kings River:

(a) Prior to April 10, as soon as progress snow-surveys indicate a minimum expectancy of runoff during April to July more than sufficient to fill the reservoir and supply the demands during April to July, releases should be increased to provide additional empty storage-space.

(b) After April 10, when complete snow-survey forecasts become available, the criteria are:

(1) To safeguard against flood, assume that the forecast may be ten per cent low with heavy early runoff as indicated by the runoff-distribution graph for early snow-melt runoff. During the time that the outcome of the runoff is in doubt, do not allow the reservoir to fill beyond a point which would result in its overflowing during the flood-period should such conditions of early runoff eventuate.

(2) To assure filling, assume that the forecast may be ten per cent high with runoff continuing until late in the season as indicated by the runoff-distribution graph for late snow-melt runoff. During the time that the outcome of the runoff is in doubt, do not allow the reservoir to empty beyond a point which would preclude the possibility of filling it under such a delayed distribution of runoff.

(3) Follow an intermediate course as long as possible--protecting against possible flood and assuring of filling. When the point is reached beyond which both conditions cannot be satisfied, the thermo-hydrograph should indicate whether the runoff is going to be less or greater than the forecast, and the operation during the last part of the season can be properly adjusted to the existing situation.

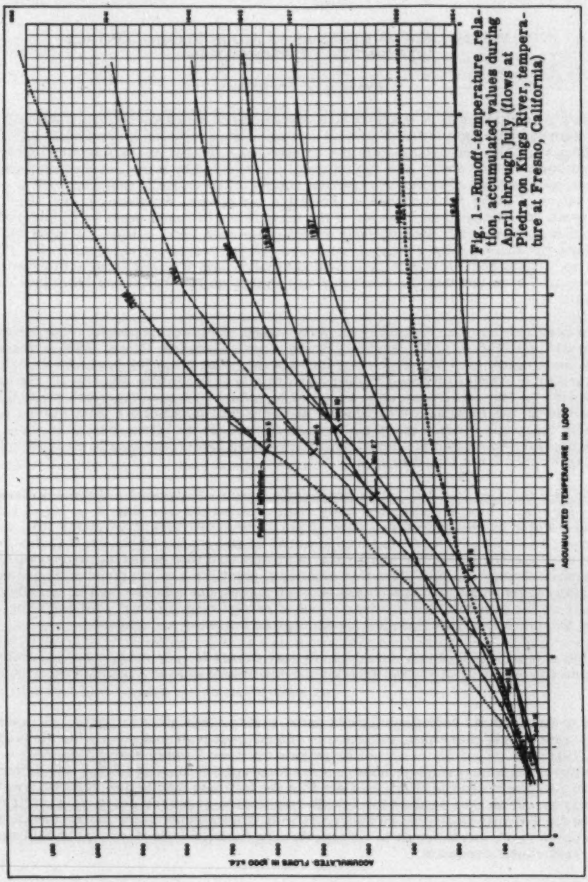

Fig. 1--Runoff-temperature relation, accumulated values during April through July (flows at Piedra on Kings River, temperature at Fresno, California)

The operating method suggested by Mr. Paget appears to have practical possibilities. No doubt, improvements in the method will be developed from time to time as additional data become available and as new techniques of interpreting and using data are developed. In studying the method, certain improvements in the technique of recognizing the start of the decline in runoff have occurred to the writer. In this connection Mr. Paget found that the time at which the runoff changes from an upward trend to a downward trend is somewhat difficult to determine readily on the thermo-hydrograph plotted from daily data because of the many minor variations. To aid in overcoming this difficulty, he prepared a thermo-hydrograph in which ten-day running means were used for both the daily temperatures and the daily runoff [see Fig. 4, p. 31, of reference above]. It was found that the flattening of the daily variations made it much easier to determine the period during which the trend of the runoff begins to decline. A study of this graph in conjunction with the

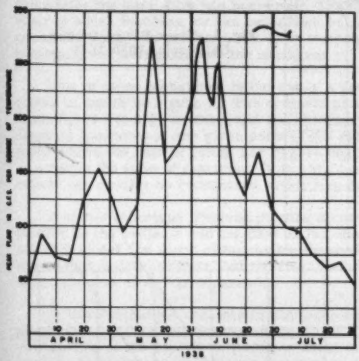

Fig. 2--Peak-flow per degree (Kings River at Piedra, mean daily temperature at Fresno, California

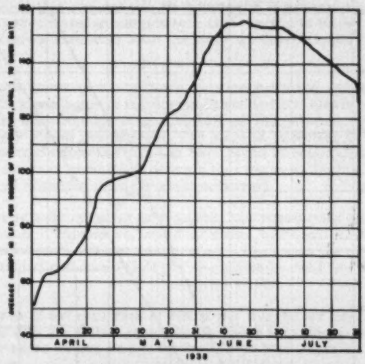

Fig. 3--Average flow per degree (flow of Kings River at Piedra, California, mean daily temperature at Fresno, California

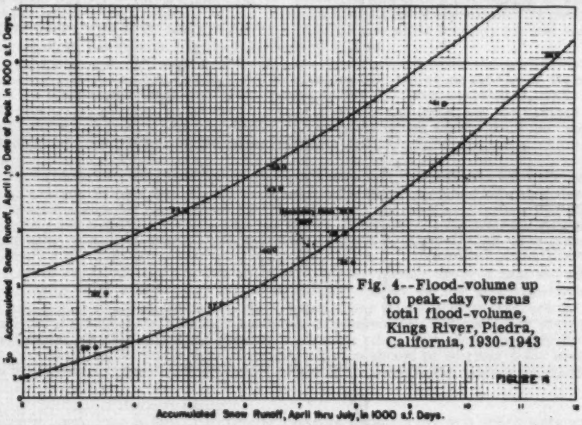
Accumulated Snow Runoff, April 1, to Date of Peak in 1000 a.f. Days.
Accumulated Snow Runoff, April thru July, in 1000 a.f. Days.
FIGURE 16

Fig. 4--Flood-volume up to peak-day versus total flood-volume, Kings River, Piedra, California, 1930-1943

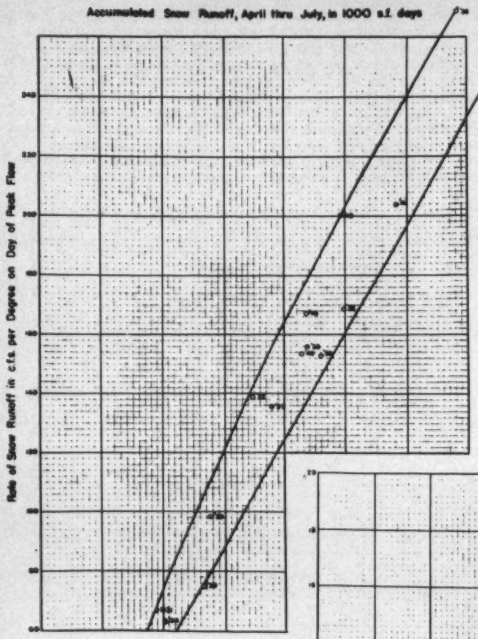

Fig. 5--Kings River, Piedra, California, 1930-1943

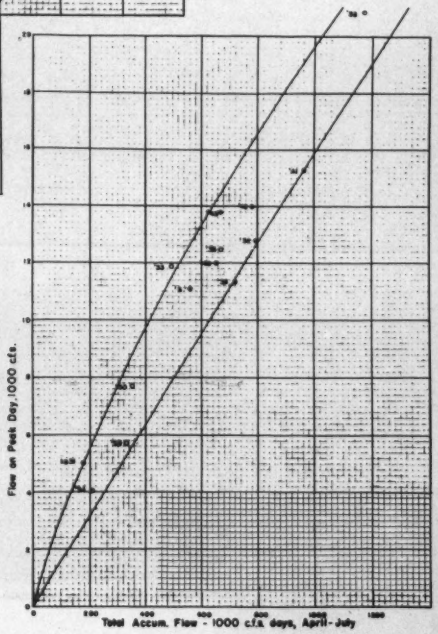

Fig. 6--Peak-day versus total flood-volume, snow-melt floods, Kings River, Piedra, California, 1930-1943

graph of daily data indicates that the decline in runoff could not be recognized until 15 to 20 days subsequent to the peak-flow. In the case of storage for irrigation-supply, such a delay might mean that in some years the reservoir would fail to fill when it otherwise could have. In the case of storage for power, such a delay would mean loss of head with the accompanying loss of valuable power.

The several techniques of recognizing the start of the decline in runoff which the writer is suggesting have only had preliminary study, but on the basis of these studies it appears that their use will shorten the time from beginning of decline to time of recognition by some 33 to 75 per cent. These techniques, except in one case, involve the concept of rate of runoff per degree of temperature. It will be shown that the maximum rate of runoff per degree occurs at or very near the day of maximum peak-flow, and that the decline in runoff can usually be recognized within five days after the peak-flow has occurred. The use of this concept can be introduced in several ways, each of which involves, or can be related to, mass-curves of temperature and runoff. In those cases involving temperature, the daily temperatures used have been the mean as determined by averaging the maximum and the minimum.

One of these techniques is the use of a double mass-curve of flows and temperatures. Such a curve is shown in Figure 1. The ordinate at any given point is the accumulated or total discharge from April 1 to a given date, and the abscissa is the corresponding accumulated temperature. The slope of the curve at any given point is the rate of runoff per degree. The point of inflection is the point where the rate of runoff per degree begins to decline and this has been found to occur usually at or near the time of maximum flow. Studies thus far completed indicate that the final decline in runoff can usually be recognized within five days after the peak-flow has occurred.

Another technique involves plotting a curve of rate of runoff per degree, the runoff-rate being plotted as the ordinate and the date as the abscissa. This curve, which is shown in Figure 2, is in effect a plot of the slope of the double mass-curve of runoff and temperature. Here also the studies completed to date indicate that the final decline in runoff can usually be recognized within five days after the peak-flow has occurred.

A third technique consists in plotting a curve of average rate of runoff per degree for any given date--that is, the average from April 1 to any given date (see Fig. 3). With this curve, recognition of the decline in runoff is about the same as can be ascertained from Mr. Paget's thermo-hydrographs--perhaps a few days earlier.

A fourth technique is a correlation of accumulated flow up to date of peak-flow and accumulated total flow from April 1 to July 31 (see Fig. 4). While the plot of this correlation is somewhat scattered it does indicate the minimum amount of accumulated flow at the time of the peak-flow to be expected for various amounts of estimated total runoff from April 1 to July 31, and thereby acts as a warning signal of the approach of the final decline in flow.

A fifth technique is a correlation of the rate of flow per degree on the day of the peak-snow runoff and the total accumulated flow from April 1 to July 31. This correlation, which is shown in Figure 5, appears to be much better than the preceding one and indicates, for various amounts of estimated total runoff from April 1 to July 31, the possible limits within which the rate of runoff per degree, on or near the date of the peak, may lie.

A sixth technique is a correlation of the peak snow-melt flow with the total accumulated flow from April 1 to July 31 (see Fig. 6). This correlation is fairly good and indicates, for various amounts of estimated total runoff from April 1 to July 31, the possible limits within which the peak-runoff may lie, and thereby acts as a warning signal of the approach of the final decline in flow, or conversely as an indication that the final decline is not yet in sight.

Each of the six techniques has certain advantages but further study of past and future floods and the collection of more extensive data are necessary before the full advantages of each can be ascertained. Additional data, which it occurs to the writer might be desirable, are the collection, during the melting-season, of continuous records of temperature and snow-line elevation at representative points throughout the melting-snow area. Such data should provide better correlations between temperature and runoff--a condition which should be of great value in making progressive predictions of runoff and in recognizing more assuredly the start of the final decline in runoff.

It may be some time before it will be practicable to obtain the data which have just been suggested. However, with the prospect that before too many years a number of watersheds in

California are going to be rather completely developed with respect to their water-resources, it seems likely that a more comprehensive collection of hydrologic and meteorological data in snow-melt-source areas will occur in some of these areas in the foreseeable future.

U. S. Engineer Office,
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DISCUSSION

L. STANDISH HALL (East Bay Municipal Utility District, Oakland, California)--Mr. Christian's paper has greatly interested me since for the past 15 years I have had to deal with the practical proposition of operating Pardee Reservoir on the Mokelumne River in California for the purpose of controlling floods, in addition to the normal function of the reservoir in water-supply and power-generation.

Floods in the Sierra Nevadas fall into two classes. The first is caused primarily by rainfall and occurs during the period, roughly, from November 1 to about April 15. The second class of flood results from the melting of snow following an increase in temperature and is limited mainly to the period from April 15 to July 15. These two classifications to some extent merge into each other, since warm rains during the early part of the season may result in a melting of snow, thereby augmenting the runoff that would normally occur from precipitation alone. On the other hand, late rains after April 15 may also augment the floods during the time of year when the runoff is caused primarily from snow-melt.

The floods of largest magnitude normally occur early in the season, prior to April 15, and are a result of a combination of precipitation and melting snow. On the Mokelumne River, the maximum known flood occurred during the winter of 1862 and probably had a peak-discharge estimated at 60,000 cfs and a total runoff of 166,000 acre-feet distributed over a period of 4-1/2 days. A careful survey and cross-sections of the river canyon below Pardee Dam were made in 1929 to locate the high-water mark of the flood of March, 1928. At the same time, marks of earlier floods were located on the canyon's slopes. From this survey, the indications were that the maximum flood at the Pardee Dam Site could not have exceeded 60,000 cfs. Ancient deposits of river sand were found in sheltered crevices along the canyon slopes at an elevation of six feet above the 30,000 cfs crest of the flood of March, 1928.

To regulate this flood-runoff, there now exists storage-capacity in Salt Springs Reservoir of the Pacific Gas and Electric Company in the upper watershed and the Pardee Reservoir of the East Bay Municipal Utility District in the foothill stretch of the stream. The maximum flood could be completely controlled if 130,000 acre-feet were available and properly distributed between the two reservoirs at the time the flood occurred. During the flood of March, 1928, 32 per cent of the runoff was derived from the watershed above Salt Springs Reservoir. In the flood of December, 1937, runoff resulted to a large extent from the melting of snow at high altitudes and 65 per cent of the total runoff was derived from the area above Salt Springs Reservoir. From this and similar data of lesser floods, it has been estimated that during a major flood a minimum of 25 per cent of the flood-water would be derived from the area above the upper reservoir. Salt Springs Reservoir is usually nearly empty during the period between January 1 and April 15, and normally would be able to impound even the maximum percentage of flood-runoff. Hence, if 60,000 acre-feet of storage space were available in Pardee Reservoir, it would be sufficient to control the maximum flood. The quantity reserved in Pardee Reservoir on the lower portion of the stream must be varied depending on the actual storage available in Salt Springs Reservoir during any particular season.

The snow-melt period used in these studies has been taken from March 1 to August 31 rather than the usual period of April 1 to July 31. This change has been made due to the fact that the floods in late March may nearly fill the reservoir; then, if the runoff from melting snow follows in quick succession, it may be impossible to increase the storage reserve during the time of the greatest snow-melt. At the other end of the scale, August 31 has been used as the final date because in many years of heavy runoff, such as 1906, 1907, 1909, and 1911, snow-runoff continued into the month of August.

The problem of controlling flood-runoff during the snow-melt period resolves itself into three parts: (1) The maximum storage-space to be retained for snow-runoff regulation; (2) the final date that storage is required for regulation of runoff; and (3) the runoff available for filling the reservoir at the end of the snow-runoff period when the flow is declining rapidly.

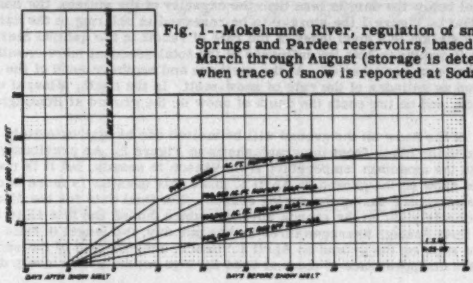
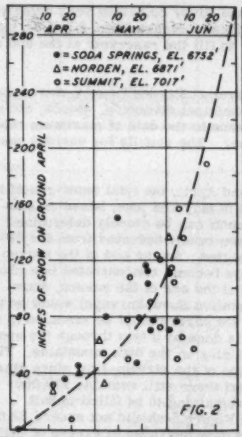


Fig. 1--Mokelumne River, regulation of snow-runoff by Salt Springs and Pardee reservoirs, based on runoff from March through August (storage is determined by date when trace of snow is reported at Soda Springs)

The graph in Figure 1, compiled from actual stream-flow statistics on the Mokelumne River, answers the first question. It is seen that the maximum amount of storage required to regulate snow-runoff substantially agrees with the storage required to regulate rain-floods. Therefore, if storage of 130,000 acre-feet has been kept available for flood-regulation during the winter months, the reservoirs will enter the snow-runoff season with ample storage to regulate the snow-runoff even during the wettest years.

In dry years the normal operation of the reservoirs would automatically draw the storage to the level required for regulation in wet years. Hence, necessity of wasting water at the end of the fall season is avoided, with the subsequent possibility of a dry year requiring all water that could be impounded or carried over from the previous year.

In making the estimate of storage-requirements, the actual discharge-capacity of outlets in the impounding dam below the spillway-level must be used. In the event that the maximum carrying



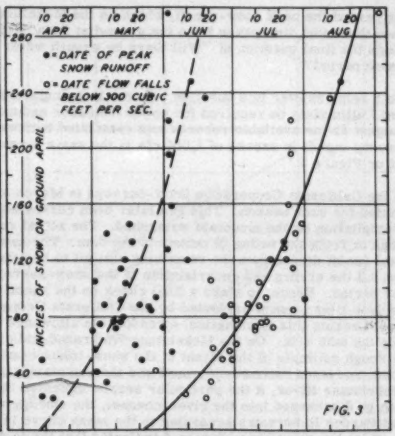


Fig. 2--Relation between snow on ground on April 1 and date of snow-melt as reported at Soda Springs

Fig. 3--Relation between snow on ground on April 1 and dates of maximum snow-runoff and of flow of 300 cubic feet per second in Mokelumne River

capacity of the channel below the dam is less than the capacity of the outlets, the smaller figure would govern. Note that in Figure 1 the storage to be reserved is relating to the date of snow-melt at Soda Springs. This station is a good index of the rate of runoff in the central Sierra during the snow-melt period, as it combines both the influence of the total seasonal snow-mantle and of the temperature during the snow-melt period. At the northern and southern ends of the Sierra, other stations should be used as an index of the rate of snow-melt. In the north, Mineral near Mt. Lassen would be a good station, and on the south the depth of snow on the ground at Huntington Lake.

The date that all of the snow on the ground will be melted can be approximately set early in the season from the Mokelumne River from the graph shown in Figure 2. As previously indicated, the snow-melt varies with the mountain temperature from season to season, but it is roughly correlated with the depth of snow on the ground on April 1, since this quantity is more variable than the rate of increase of temperature during the spring season. The final date for the disappearance of snow can be more accurately set as the season advances since during the last 15 to 30 days the rate of snow-melt at Soda Springs averages three inches per day, the length of time increasing with greater depths of snow on the ground on April 1. Hence, near the end of the snow-melt season, the date for the disappearance of snow at Soda Springs can be very closely determined.

As this time approaches, the engineer in charge of operations at a reservoir becomes interested in the date that the peak-discharge will be reached and also in the date that the snow will be completely melted and the normal summer flow will be established (see Fig. 3). The remaining unfilled portion of the reservoir-storage reserved for flood-control must be filled during this interval. Too early filling of the reservoir may result in a large flood-discharge over the spillway. On the other hand, too late filling may leave the reservoir below spillway-level at the end of the snow-melt. The last date of occurrence of floods requiring regulation (4500 cfs on the Mokelumne River) correlates reasonably well with the total volume of runoff during the period from March 1 to August 31 (see Fig. 4). The date that storage-space must still be reserved will naturally vary from season to season due to variations in temperature or due to late storms in the mountains. If the daily reports on these factors are closely followed during any particular season, the graph then furnishes a reasonable guide. On the Mokelumne Watershed the daily temperatures at Salt Springs Reservoir are a reliable index of the temperatures in the high Sierra and the precipitation is practically the mean for the entire upper drainage-area. The heaviest snow-melt usually follows the first pronounced seasonal temperature rise in the mountains.

Having passed the peak snow-runoff, which on the Mokelumne River coincides very closely with the date that snow disappears from the ground at Soda Springs (compare Figs. 2 and 3), the season brings the final question of "Will there be enough water to fill the reservoir at the end of the snow-melt period?"

Figure 5 helps answer this question. On the Mokelumne River at Pardee Dam, a maximum 1,000 cfs will ultimately be required for power-releases and municipal diversion. Hence, the runoff from August 31 for available records was cumulated backwards to the date of maximum runoff and likewise the runoff in excess of 1,000 cfs in the same manner. The results for various seasons are plotted on Figure 5.

From the California Cooperative Snow-Surveys in March and April, the total snow-runoff has been estimated for each season. This has later been corrected in May and June, based on subsequent precipitation on the mountain watershed. The actual runoff can be closely determined from gagings or from the rating of outlets in the dam. The known runoff deducted from the estimated total runoff determines the remaining amount to be expected. As the end of the season approaches, all the errors and uncertainties of the snow-surveys become concentrated in a shorter and shorter period. Hence, to make a final check on the runoff at the end of the season, snow-surveys on June 1 (at present neglected by the California Cooperative Snow-Surveys) would be of great value. Lacking this information, a reasonable allowance for errors must be assumed in order to be on the safe side. On the Mokelumne Watershed, this is done by a trip through the upper area and a rough estimate of the extent of the snow-banks remaining on the high mountains. Then, with the final corrected estimate of runoff and the summarization of the stream-flow since March 1 on the Mokelumne River, if the particular season indicates that there still remains 120,000 acre-feet to be discharged into the river-channel, the storage remaining to be filled in Salt Springs and Pardee Reservoirs according to the mean curve in Figure 5 should not exceed 33,000 acre-feet. If, at the same time, Figure 4 indicates that the last date for flows in excess of outlet-capacity has been past, the storage-space to be filled can be reduced to a smaller quantity immediately.

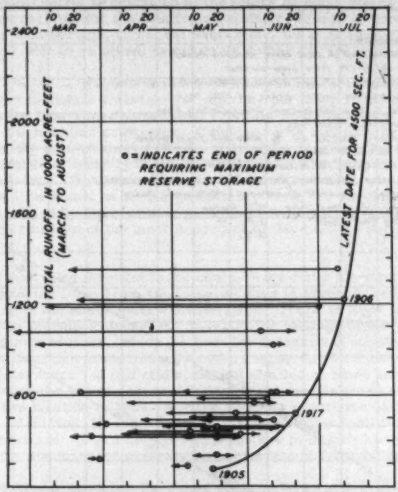


Fig. 4--Mokelumne River at Clements, snow-runoff period for flows exceeding 4500 second-feet

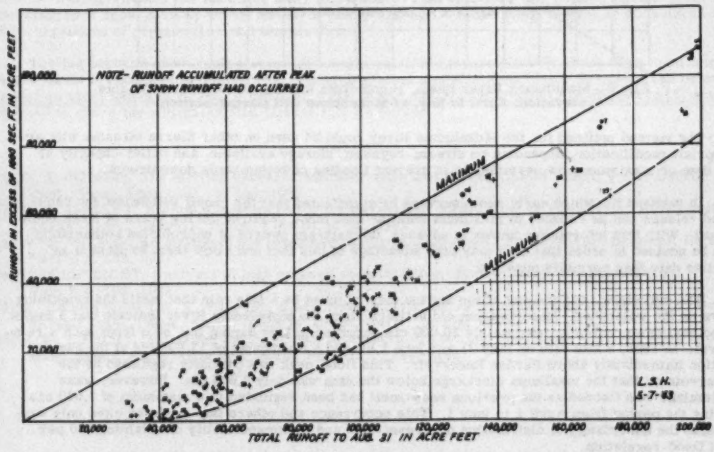

RUNOFF IN EXCESS OF 1000 SEC. FT. IN ACRE FEET
NOTE- RUNOFF ACCUMULATED AFTER PEAK OF SNOW RUNOFF HAD OCCURRED
MAXIMUM
MINIMUM
L. S. H.
5-7-43
TOTAL RUNOFF TO AUG. 31 IN ACRE FEET

Fig. 5--Mokelumne River at Pardee Reservoir, total runoff at end of snow-melt season compared with runoff in excess of 1000 second-feet

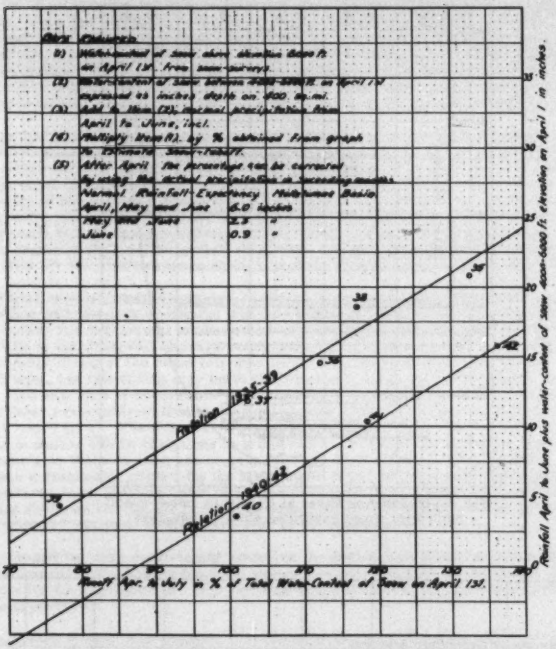

Runoff Apr. 1 to July in % of Total Water-Content of Snow on April 1st.
Runoff April to June plus water-content of snow above 6000 ft. elevation on April 1 in inches.
Relation 1938-39
Relation 1940-42
.38
.32
.30
.42
.31
.20

Fig. 6--Mokelumne River Basin, runoff from melting snow above 6000-foot elevation, April to July, at Mokelumne Hill Gaging-Station

The method outlined for the Mokelumne River could be used on other Sierra streams with appropriate modification, depending on stream-regimen, storage available, and outlet-capacity at the dam or maximum flow permissible to prevent flooding of bottomlands downstream.

In seasons for which early snow-surveys have indicated that the runoff will be low, the regulated release can be reduced to maximum smaller than those required during years of large snow-runoff. With this information known in advance, downstream owners of unprotected bottomlands can be advised in order that they may take advantage of this fact and allow them to plant at an earlier date than normally possible.

The estimates near the end of the season may be upset by a late rain that melts the remaining snow on the watershed. Reports from old settlers along the Mokelumne River indicate that a major flood having a crest of approximately 20,000 cfs occurred in May during the '80's from such a rainstorm. In 1943, a late rain on May 31 and June 1 caused a flood-peak of 12,000 cfs at the gaging-station immediately above Pardee Reservoir. This flood-peak was partially regulated by the reservoir so that the maximum discharge below the dam was only 6,000 cfs. However, some bottomland was flooded as the previous snow-melt had been regulated to a maximum of 3,500 cfs during the period from April 1 to June 1. This occurrence and others that might be cited only emphasize the uncertainty of distribution of stream-flow and the impossibility of obtaining 100 per cent flood-regulation.

In conclusion, if flood-control is practiced in the future on many Sierra streams, the need will become more greatly appreciated for the publication of daily records of snow on the ground at more Sierra locations than at Soda Springs; and at the same time, the need for a final snow-survey and runoff-estimate on June 1 will be realized, particularly during the years of large snow-runoff.

RAY K. LINSLEY, JR. (U. S. Weather Bureau, Sacramento 9, California)--The operation of reservoirs in the western mountain drainages for multiple purposes requires two basic types of forecasts. The first is the long-range or seasonal forecast which indicates the anticipated seasonal runoff-volume from the mountain snow-pack. Combined with this may be forecasts of the probable peak-flow and date, the date of decline to non-critical flows, and other elements of the runoff-pattern. Such forecasts are necessarily based on statistical analysis of snow-survey and of precipitation- and runoff-data. Whether a factor of safety will be used as suggested by Mr. Paget, whether the operation will be based on normal probability or on the envelope of the worst possible conditions, will be determined by the operating policies of the controlling agency, which will in turn be fixed by the requirements of the most important of the multiple purposes for which the reservoir is planned.

The second type of operating forecast is the short-range river forecast which can supply a definite prediction of expected flows from two to seven days in advance, depending on the weather conditions and the nature of the basin under consideration. There is little need to turn to statistical data or the proposed thermo-hydrographs to verify the passage of the peak-runoff when it may be predicted several days in advance. Many methods for forecasting stream-flow from snow-melt have been presented. Wilson has presented a procedure using double mass-curves of degree-days and runoff [see 1 of "References" at end of discussion] similar to those shown by Christian. A simple procedure involving the use of degree-days and a degree-factor was presented by the writer [2] at the Corvallis Meeting in 1943. A more complex procedure using more rational snow-melt formulas is given by Wilson [3], while Light [4] presents snow-melt formulas derived by thermodynamic considerations. In ordinary practice the use of degree-days will prove to be the simplest method and fully adequate for ordinary requirements of forecasting.

In any of the forecasting procedures the use of degree-days alone is not sufficient to define the runoff-hydrograph. The amount of snow melted on any day is a function of the temperature and the area of the snow-pack subjected to melting conditions. The more elaborate formulas also include humidity, wind, and solar radiation. The thermal quality [5] of the snow must be considered, either through direct measurement or by use of a variable degree-day factor. The shape of the outflow-hydrograph and the resulting daily increments of stream-flow are further altered from the increments of snow-melt by the influence of valley-storage. These factors must be considered in any correlation of stream-flow and temperature.

The lag between snow-melt and runoff usually permits forecasts two to three days in advance on the basis of observed temperatures. Using predicted temperatures, these forecasts can be extended to about seven days and, if desired, a statistical analysis of trends of temperature [6] may be used to carry the estimates still farther into the future.

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THE UTAH SNOW-MOBILE

George D. Clyde

The manpower shortage resulting from the war has given impetus to the development of power-driven transportation for use over deep snow-cover. Furthermore, the need for such transportation in winter rescue work in mountainous regions in connection with air-transportation and war maneuvers has greatly increased the interest in such equipment.

The Utah Snow-Mobile was developed originally to provide transportation over inaccessible watersheds in connection with snow-surveying and stream-flow forecasting. The snow-survey courses are, for the most part, inaccessible to open winter highways and can be reached only on foot or by means of power-driven vehicles which can operate over all kinds of snow across fairly steep transverse slopes and on fairly steep grades.

Many different types of machines have been developed looking toward winter transportation over snow-cover. Snow-cover is not stable and changes radically throughout the winter season. Normally, when the snow first falls, it is light and powdery and has little supporting power. As the snow consolidates, its density increases and its supporting power increases greatly. This is particularly true if the season has been characterized by alternate freezing and thawing. Oftentimes the snow-cover becomes very hard on the surface due either to freezing after a thaw or due to high winds. In the timbered areas the snow-cover does not consolidate well and its supporting power is very much less than in the open parks where the wind and the Sun have a marked effect on its stability. As the temperature changes from morning until night, the supporting power of the snow changes radically. It has been extremely difficult to design a power-driven vehicle which would operate satisfactorily under all of the changing conditions of temperature and snow-stability.

In spite of the many difficulties, many types of machines have been developed, all of which are more or less successful on a hard-crusted snow-cover and level or rolling topography. However, when the topography is rough and the route of travel is across heavy transverse slopes, or the snow is light and powdery, most of the machines experience considerable difficulty.

Of the machines developed to date for transportation across snow-cover, the following types are most common: (a) Vehicles mounted on skis and driven by airplane propellers; (b) vehicles mounted on skis and driven by spiral worms operating in the snow; (c) combination ski and driving track; (d) driving tracks pulling a sled.

These types are described briefly in the Transactions of 1942 of the American Geophysical Union [pp. 424-428]. All of these types have their advantages and disadvantages, but none of them appears to be able to successfully operate under all conditions of snow and on the longitudinal and transverse slopes usually encountered in winter travel over the high watersheds.

The ideal vehicle for winter transportation over deep snow-cover is one which combines lightness with a positive driving action and a positive steering mechanism. The vehicle should lend itself to the construction of a cab for the protection of the passengers and equipment.

The weight of the vehicle empty should not exceed one-half pound per square inch which is about the unit-weight of a man on a pair of snow-shoes. The ordinary caterpillar tractor, therefore, is much too heavy. Furthermore, the machine should be so designed that the snow will not stick to the tracks no matter what the condition of the snow-cover.

The propeller-driven vehicle has several serious disadvantages among which are the danger to the passengers of the whirling blade, the necessity of operating in the open, away from trees and brush, and the difficulty of starting the vehicle when the temperature of the snow is such that it sticks to the runners.

The tractor principle seems to offer the most promise for winter transportation over deep snow-cover. The ordinary tractor has many inherent disadvantages which had to be overcome. The first was the weight. This was overcome in the Utah Snow-Mobile by mounting wide, light metal tracks on the rubber tires of an ordinary automobile. These tracks were made wide so as to reduce the unit-load on the snow-cover. It was early discovered that snow would pack between the tracks and the wheels, causing stalling and failure of the tracks. This difficulty was overcome by designing a split track with the wheel operating between the two segments of the track. This arrangement provided a self-cleaning device which prevents the accumulation of snow between the tracks, regardless of the condition of the snow or the depth to which the vehicle sinks in the snow-

Fig. 1

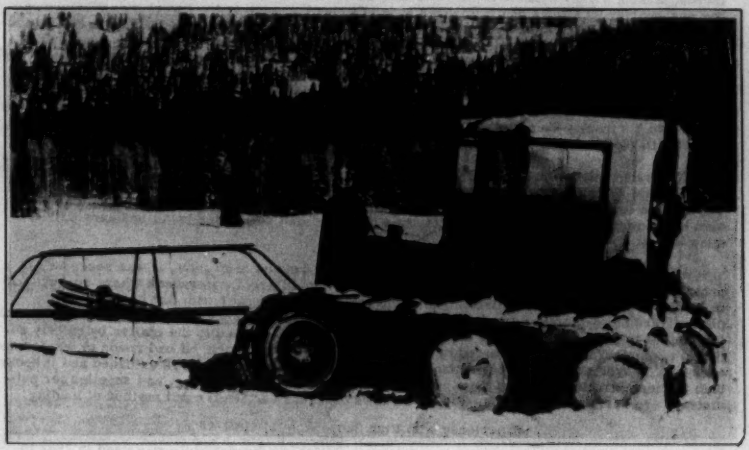

Fig. 2

cover. Figure 1 is a close-up of the driving wheel showing how the snow tends to clog the tracks. The split track breaks up the snow with each revolution of the wheel.

The conventional method of steering a tractor was found to be impracticable because when one track was stopped the moving track would dig in and tend to overturn the vehicle. This method was found to be quite satisfactory on hard-crusted snow, but entirely impracticable in soft snow. Therefore, a different method of steering the vehicle had to be devised. This was worked out satisfactorily by projecting in front of the vehicle a movable runner operating on a fixed swivel at the end of a frame which was rigidly fastened to the chassis of the Snow-Mobile. This runner was operated through a cable-chain mechanism fastened to the steering column of the vehicle. This runner has proven to be very satisfactory in all kinds of snow. Furthermore, the frame to which the runner is attached provides a place for carrying the miscellaneous gear and the passenger load. Figure 2 shows the Utah Snow-Mobile with the guide-runner attached. Figure 3 shows the cable-chain connection of runner to the steering column.

The principle of the split track and the guide-runner was developed by WALTER HANSEN, a mechanic of Ephraim, Utah, and these are the two basic principles which make the Utah Snow-Mobile a successful vehicle for transportation over deep snow-cover.

The first Snow-Mobile was constructed in the shops at the Utah State Agricultural College in the spring of 1942, using such equipment and material as was available in used-car lots and in scrap piles. The chassis used was a cut-down section of the frame of a Chevrolet automobile. A six-cylinder Chevrolet motor, model of 1933, was used for power. A four-speed truck-transmission was used with a rear end consisting of a ring-and-pinion gear having an approximate ratio of 7 to 1. Figure 4 is a close-up of the rear end showing the driving wheel with track.

The rear wheels are the driving wheels. All wheels are equipped with high-pressure tires (4-1/2 by 21 inches). The front axle is attached rigidly to the frame. The center wheels are suspended on springs and set so that they ride about four inches below the front and rear wheels. These wheels tend to act as a pivot about which the guide-runner turns the vehicle. Figure 5 shows the wheel alignment.

The tracks were constructed of ten-gage black iron, cut so that the links are nine inches long. Each of the track segments was corrugated 1-1/2 inches deep with three per strip. The strips are ten inches wide and nine inches long. The width between the two strip-segments of the track is six inches, making a total width of track of 26 inches. At the end of each link of the track a transverse bar one-quarter inch thick and two inches wide is welded on edge to the end of the link-segment. The link-segments are fastened together by an ordinary hinge-construction, welded to the respective ends of the adjacent links. The transverse bars welded to one end of each link bear on the rubber tires of the driving wheels and the traction is obtained by friction between these transverse bars and the rubber tires. The entire track-mechanism can be adjusted by means of a tightener welded to the frame of the chassis at the front end. Welded onto the transverse bars are guides which keep the tracks properly centered on the wheels. By driving from the rear end, the tires wedge into the tracks, thus giving a greater tractive effort. The torsional effect of the tracks tends to lift the front end of the vehicle out of the snow.

The distance between the front and rear wheels is 7.4 inches and the diameter of the wheels is 21 inches. This provides a total area of track in contact with the snow of 4200 square inches. The vehicle empty weighs 3000 pounds, or seven-tenths pound per square inch of area in contact with the snow-cover. This is almost the same unit-load that is carried by an ordinary pair of snow-shoes.

Although the Snow-Mobile will operate over bare ground or deep snow, it was necessary to provide quick easy transportation to the snow-line on the different watersheds where surveys had to be made. This was accomplished by building a four-wheel trailer with flat bed and loading planks. The Snow-Mobile is loaded by driving it up the loading planks onto the trailer. The runner is clamped to the track on side of the cab. The entire vehicle is tied to the trailer by quickly adjusted clamps. The trailer is towed by a GMC four-speed panel truck. If bad roads or grades are encountered over which the truck cannot tow the trailer, the Snow-Mobile is unloaded and it hooks onto truck and trailer and tows them. The survey-party, its gear, bedding, and supplies for subsistence are carried in the truck. Figure 6 shows the truck and trailer and method of loading.

Experience with Utah Snow-Mobile, 1942-43

Year 1942--Without the benefit of preliminary trials, the Snow-Mobile was used in 1942 to reach the snow-courses at Tony Grove Lake, Franklin Basin, Monte Cristo Ranger Station, Snow

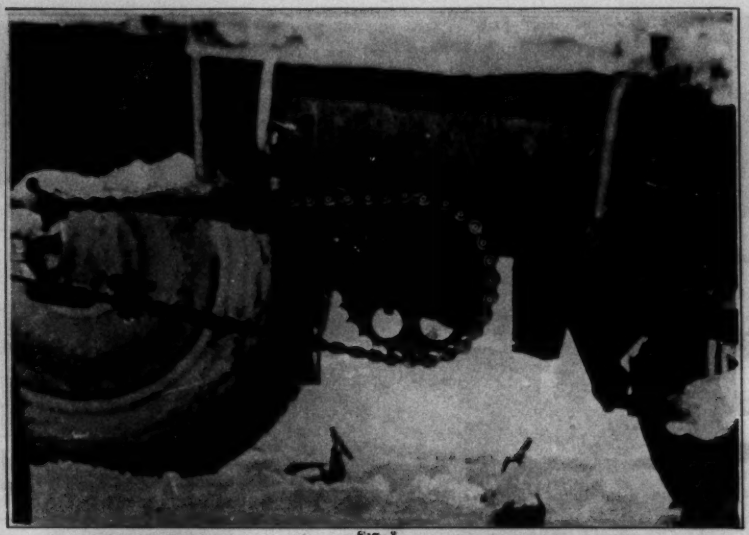

Fig. 3

Fig. 4

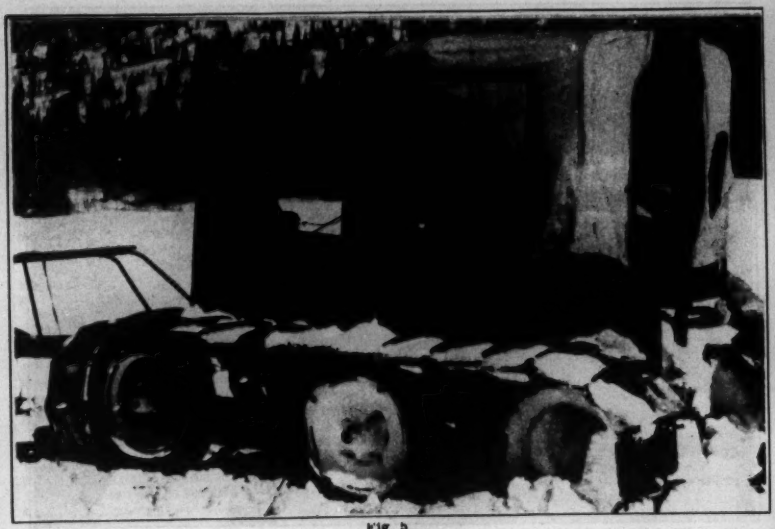

Fig. 5

Fig. 6

Fig. 7

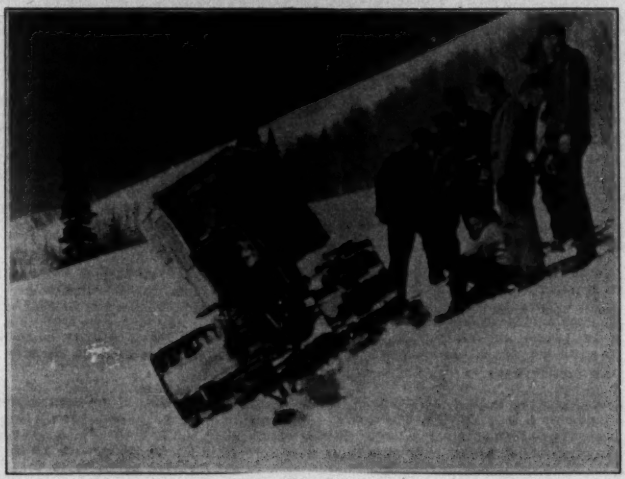

Fig. 8

Basin, Head of Bear River, and Head of Provo River. These courses range in elevation from 6,000 to 10,500 feet. The total trip involved over 700 miles of travel and the actual distance covered by the Snow-Mobile exceeded 175 miles. Snow of all kinds and grades up to 25 per cent were encountered. The machine returned from each survey under its own power.

It took two men seven days with the Snow-Mobile to make the survey which normally requires 48 man-days of time.

Year 1943--The year 1943 was one of unusually heavy snow-cover. The Snow-Mobile was again used without modification to measure all of the courses covered in 1942 and, in addition, the courses on the Gooseberry Watershed. The snow-cover ranged in depth from three to 12 feet and

the elevation from 6,000 to 11,000 feet. In many instances the mountain roadways were completely buried in snow and often wind had drifted the such to such an extent that difficult transverse slopes were encountered.

The total distance travelled by the snow-survey party was approximately 1,000 miles, of which some 300 miles were travelled by Snow-Mobile. These surveys were completed in ten days without mechanical difficulty, although in many instances it was necessary to leave the mountain roads and travel along the bottoms of the canyons over the stream-channels. Normally, this survey would have required a total of 64 man-days. It was accomplished by using the Snow-Mobile in 20 man-days.

In the early fall of 1943 a party was making moisture-determinations of the soil at the Monte Cristo Ranger Station at elevation 10,000 feet. The party was caught in a blizzard, and before it could get off the mountain the car was buried in four feet of snow. The party walked out 27 miles and got the Snow-Mobile and pulled the car out. Later during the same winter the United States Army was experimenting with a ski-propeller-driven sled in the Ant Valley Area of Blacksmith Fork Canyon. The sled tipped over and the men could not get it out and asked for the Utah Snow-Mobile to get them out. The Snow-Mobile was taken over 12 miles of rolling topography and it brought out all the Army gear and the snow-sled in one trip. Figure 7 shows the Snow-Mobile towing the snowplane.

In order to test the Snow-Mobile under the most adverse conditions, it has been operated in very light snow with heavy loads, up steep grades, and across steep side slopes. One trip was made to Tony Grove Lake with a load of 11 men. The maximum grade was about 15 per cent. On this trip steep grades and heavy cross slopes were encountered. Figure 8 shows a typical heavy cross-slope.

On another trip to Tony Grove Lake a stream-crossing was necessary. The snow which was arched over the stream broke through, dropping the Snow-Mobile to the stream-bed (see Fig. 9). It easily pulled itself out.

The Snow-Mobile readily traverses the ordinary mountain topography which is crossed by mountain roads. Where the roads go along side-hill cuts and the snow drifts over the cuts, it is often necessary to leave the roads and follow up the creek-beds. Figure 10 shows a typical Snow-Mobile track up the creek-bed; the road is on the hillside to the left. Figure 11 is the shelter-cabin at Franklin Basin, the site of one of these snow-courses. Figure 12 is the Utah Snow-Mobile in Franklin Basin alongside the snow-course. A speed of ten to fifteen miles per hour is common under the conditions shown here.

The Monte Cristo Ranger Station is at elevation 10,000 feet. The snow here on April 1, the date of the annual snow-survey, is about 5,000 feet. The distance from the snow-line to the ranger station is approximately 30 miles. The road up this mountain meanders around side hills and along and over ridges. Drifting along ridges makes travel difficult. Where such drifts are encountered it is often necessary to leave the road and go through timber. Figure 13 shows the Monte Cristo Ranger Station under a heavy cover of new snow. Note the depth in the snow to which the Snow-Mobile sinks.

The snow-courses on the headwaters of the Price and San Pitch rivers are located at elevations above sea-level from 8,000 to 10,500 feet. The Snow-Mobile easily transversed the steep grades necessary to reach the top of the Horseshoe at elevation 10,500 feet. The snow-surveys which normally take three men three days to make were completed in one day with the Snow-Mobile. On the return trip the forest-ranger got off the trail and directed the party down a ravine. The ravine became very narrow and rough with steep side slopes. It became impossible to turn around, so the entire return trip was made down a steep narrow ravine, over low waterfalls and beaver dams. The Snow-Mobile went through under its own power and came out with only a few damaged track-guides.

At the completion of the surveys in 1943 the Snow-Mobile was dismantled and carefully inspected. It was found that the universal joint was badly worn and had to be replaced. This condition suggests that perhaps a worm-drive or a reduction in the angulation of the drive-tube will be necessary in future models.

As a result of two years' experience it is believed that when strategic materials again become available it will be possible to greatly improve the present model of the Snow-Mobile. For example, the engine should have a full-pressure oiling system and the tracks can be made of lighter

Fig. 9

Fig. 10

Fig. 11

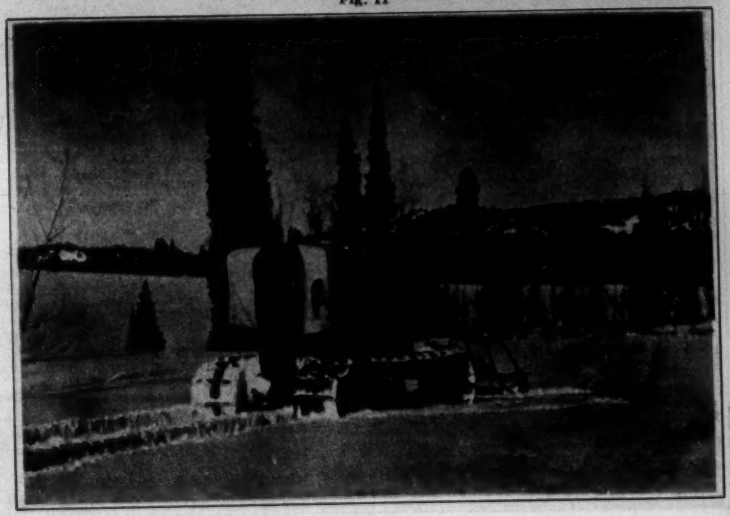

Fig. 12

Fig. 13

metal. The frame can be made of aluminum. The wheel guides should be made of flat iron and wider. The front axle should be fastened rigidly to the frame with individual tightening devices on each track. The guides-runner should be hinged to permit loading without dismantling.

When materials again become available, an attempt is going to be made to construct a machine, using the principles utilized in the present Utah Snow-Mobile, but which will weigh not more than 1500 pounds as compared to 3000 pounds--the present weight. The following is a brief summary of the physical features and operating characteristics of the Utah Snow-Mobile.

Physical features of Snow-Mobile

Chassis: Chevrolet automobile
Engine: Six-cylinder 1933 Chevrolet, 65-h.p. splash lubrication, water-cooled (forced lubrication-system desirable)
Transmission: Standard four-speed truck
Rear end: Differential type, ring gear and pinion; ratio, 7:1; worm-gear desirable, ratio 13:1
Wheels: Standard automobile, UN 21 by 4-1/2 high-pressure tires
Tracks: Split type; segments ten inches wide spaced six inches apart with transverse bars on edge one-quarter by two inches welded to end of track-links; track links four inches long, ten inches wide, three corrugations one and one-half inches deep per link; hinges welded to adjacent ends of links; links made of 10-gage black iron; total width 26 inches
Track-tightener: Acme thread-screw attached to center of front axle
Clearance: Front axle, 20 inches; rear axle, ten inches
Total width: Seven feet
Total length: Ten feet (exclusive of runner)
Brakes: Drum-type, individually hand-operated
Guiding-runner: Frame, ten feet six inches long, rigidly attached to chassis; runner, six feet by six inches, pivoted at front of frame
Cab: Steel-tube welded construction, covered with canvas
Total weight empty: 3,000 pounds

Total area of track: 4,200 square inches
Weight empty per square inch: 0.7 pound (average for man on snow-shoes is 0.6 pound per square inch)
Capacity: Three men and equipment

Operating characteristics

Shifting gears: Comes to dead stop at each shift; hard on gears; need fluid drive
Steering: For soft snow use guiding-runner; needs 50-foot radius to turn; for crusted snow use either guiding-runner or hand-brakes
Grades: Any road-grades up to 25 per cent
Transverse slopes: Hard snow, 35 per cent; slips in soft snow on slopes above 15 per cent
Speeds, miles per hour: Crusted snow, 20 to 30; soft dry snow (penetration 12 to 18 inches), 3 to 5; soft wet snow (penetration 8 to 12 inches), 5 to 8; very soft dry snow (penetration 20 to 24 inches), 2 to 3
Consumption of gas, miles per gallon: Crusted snow, 5 to 8; soft dry snow, 2 to 3; very soft dry snow, 2

Transportation of Snow-Mobile

(1) Four-wheel flat-bed trailer with loading planks; runner mounted on side of cab; Snow-Mobile driven up on trailer under its own power and anchored to trailer-bed
(2) Trailer towed by GMC four-speed panel-body truck
(3) Beds, gear, and supplies for subsistence of snow-survey party carried in truck

Utah Agricultural Experiment Station,
Logan, Utah

WINTER TRANSPORTATION IN THE HIGH SIERRA BY SNO-MOTOR

W. A. Lang

A report on the Southern California Edison Company's operation of the Sno-Motor up to the end of 1941 was presented at the Pasadena Meeting of the Western Snow-Conference on January 16, 1942. In the last two years additional operating experience has been gained as outlined in the following paragraphs.

Since January, 1942, the Sno-Motor has been driven 956 miles with an output of 1.09 miles per gallon of gasoline. The total operating time was 245 hours. The operating cost exclusive of depreciation and the charge for the driver but including gasoline, oil, and repairs has averaged $1.26 per mile for the last two years.

The value of the Sno-Motor to the Southern California Edison Company has been amply demonstrated. In the early spring of 1942 it was necessary to transport 35,000 pounds of 12-gage steel sheets, 48 by 96 inches in size, 31 miles from Big Creek to the Florence Lake Dam. The sheets were to be used in repairs which had to be completed before the spring runoff filled the reservoir. These steel sheets were hauled across Kaiser Pass at elevation of 9,300 feet between April 30 and May 13 while the roads were still covered with up to 105 inches of snow. In addition to handling the steel during the spring of 1942, the Sno-Motor transported the repair-crew with necessary supplies and food during the months of March, April, and May of 1942 and 1943. The maximum snow-depth during these periods was 161 inches.

On account of the illness of one of the Florence Lake headworks tenders, an emergency trip over the same route was made in January, 1944. A man to replace him together with complete winter supplies was transported on the inbound trip and the headworks tender's wife and personal belongings brought out on the return trip. The round trip was made January 11 and 12 with no difficulty whatever.

Our experience indicated that this type of vehicle is more desirable than smaller types which cannot carry a sufficient load.

Taking the operation of the present Edison vehicle into consideration during the period owned by the Company, everyone connected with the operations of the power-plants seems to be fully sold on its value, but like every other type of machinery new developments and improvements will no doubt make models now in operation obsolete.

The designer of the Sno-Motor, TED FLYNN of Portland, has developed a new type very similar to the Edison Company's vehicle, except that it is a two-track machine, is considerably lighter, and has a somewhat smaller capacity. The two tracks permit much quicker steering.

It is our understanding that one of these new types has been delivered to the Bonneville Power Administration for maintenance of its power-lines. The design is expected to incorporate on the vehicle some sort of winch by which the repair-crews might be able to hoist such repair-parts as necessary to the top of the transmission-towers when needed under snow-conditions.

The designer of the new Sno-Motor, two-track model with sled, makes the following claims for improvements: (1) Easier and quicker maneuverability in tight places; (2) with greater track-area and relatively lighter weight, it has greater tractive ability on soft snow and steeper grades; (3) the new track-system mounting provides greater freedom for tracks and consumes noticeably less power; (4) has provision incorporated for installing a hoisting-winch and set of fair-leads; (5) increased cab-room with no increase in weight and added good-sized compartment for baggage; (6) an outstanding advantage is that the machine can be operated without the sled when necessary, and when operated alone should have greater ability for grades, etc., and also for making pioneer trails.

The Army has become very much interested and is proceeding to build a number of this type of equipment.

Southern California Edison Company,
Los Angeles, California

APPENDIX--REPRINTS OF ARTICLES BEARING ON SNO-MOTOR

(The following articles entitled "Snow-drifts are 'Sno-Motor's' meat" and "'Sno-Motor' trolley" are reprinted from Southern California Edison Company's Edison News (p. 9 and p. 15, January and March, 1944, issues, respectively.)

Snow-drifts are Sno-Motor's meat

It looks like a cross between an old-style Army tank and a sea sled--but regardless of the miscellaneous qualities of its appearance, the Sno-Motor is a most efficient means of winter transportation in the snowbound High Sierra areas of the Big Creek Project.

For about six months of an ordinary year, snow closes the road above the town of Big Creek. Snow-shoes or skis used to be the only means of access to Huntington Lake, Mono Creek, Bear Creek, Florence Lake, and other points in that region. The Sno-Motor was the answer to the need for a quicker and safer means of transportation.

It also provides the important advantage of taking away the threat of accident or illness which used to attend those who are snowbound at Florence Lake in the winter.

Designed by a United States Forest Service engineer and built in a Portland factory, the Sno-Motor is one of only five in use in this country. The Forest Service uses one at Mount Hood, Oregon. Others are used for pleasure purposes at Sun Valley, Idaho, Estes Park, Colorado, and Yosemite Valley. At present the Army is investigating the possibilities of the machine for military service in snowbound regions.

The Sno-Motor will travel in almost any kind of snow, and goes about any place that can be reached by snow-shoes. It is reputed to be capable of negotiating a grade of 50 per cent, but we have had no occasion to use it on anything over 30 per cent, which it ascends and descends satisfactorily with a full load of two and a half tons.

The power-end of the unit operates very much the same as a caterpillar tractor except that it has only one large, endless-type crawler-tread assembly that extends the entire width (56 inches) of the machine and runs completely around it. The open-type crawler prevents ice from building up between the treads and yet permits compaction of the snow between the treads by the bottom plate of the tractor, thereby developing maximum traction obtainable from the snow.

The crawler-assembly is made up of duraluminum angle treads, mounted on three link-belt endless chains, which, in turn, run in tracks attached to the frame of the tractor. Snow-strippers are attached to each tread to prevent snow and ice from building up on the body of the tractor and on the treads themselves.

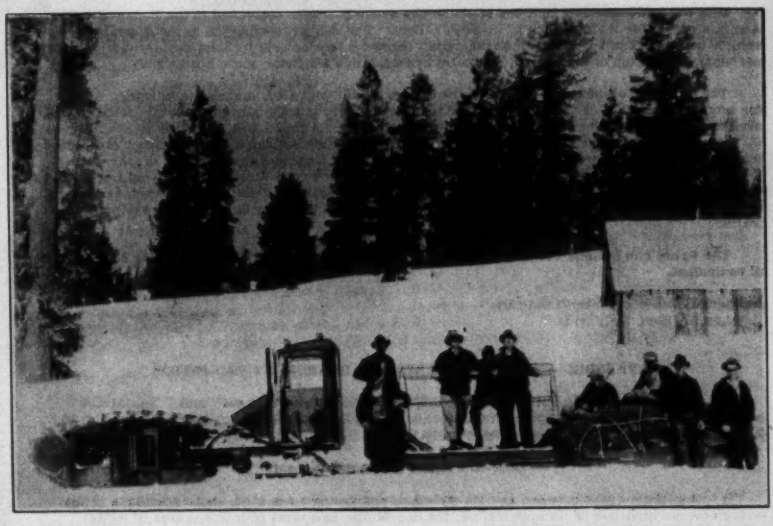

Fig. 1--The Sno-Motor packs a he-man load

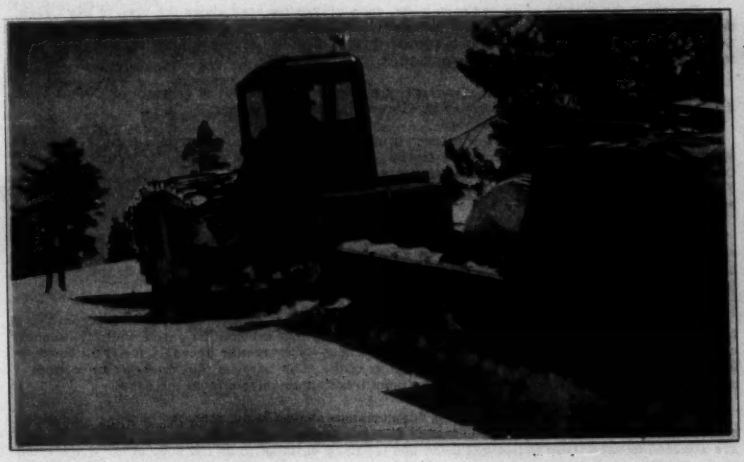

Fig. 2--The load is packed in the sled-trailer

Fig. 3--Operator's cabin is perched up back out of way of circulating track

Fig. 4--On steep side-hills Sno-Motor benches itself out a flat roadbed

Fig. 5--Sideling canyons bother Sno-Motor not at all

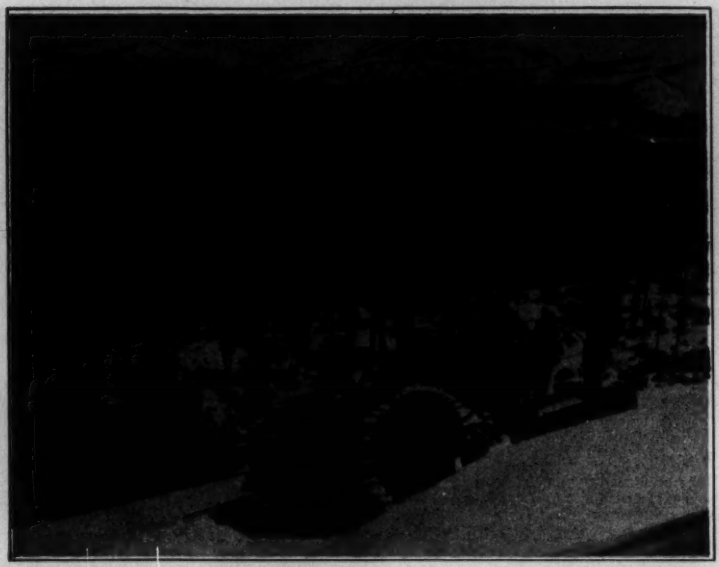

Fig. 6--A cold ride for passengers but Sno-Motor climbs hills faster than a man can walk

The engine, transmission, and drive mechanism, along with the fuel tank and radiator, are mounted on the bottom plate of the tractor and give it an extremely low center of gravity and excellent stability for side-hill travel.

The machine is powered by a 95-h.p., six-cylinder gasoline engine with a special, double float airplane-type carburetor suitable for operation in almost any position the machine may be thrown into in a day's run. It also has an especially designed oil-pan and pump to insure lubrication at almost any angle. Its 50-gallon gasoline tank makes it possible to make an approximate 12-hour run without refueling. Its speed ranges from half a mile in low gear up to 20 miles in high gear.

The operator sits in a little cab mounted on the rear of the tractor. He is placed there for good visibility in rough terrain. The cab and control-mechanism are attached to the body of the tractor by spandrel arms extending around the crawler-assembly.

The sled steers the unit in much the same manner that a rudder steers a boat. Most caterpillar tractors are guided by braking one crawler and driving on the other, but this is not possible on the Sno-Motor, since it has only one crawler. On each side of the sled is a steel plate approximately four feet long and extending down into the snow about six inches, comparable to the rudder on a boat. The sled is connected to the rear of the tractor through a spandrel pipe attached to a ball-and-socket joint. This permits independent movement of the sled, both horizontally and vertically, with respect to the tractor end of the unit. A small windlass driven by planetary gears from the engine is located on each side of the tractor. Steering is accomplished by taking up on one of the winch cables attached to the front corners of the sled and slacking off on the other winch cable, thus changing the angle between the motor and the sled.

The sled is about five feet wide and 18 feet long. Two seats extend about half way along each side and accommodate 12 passengers.

The Sno-Motor exerts a weight of only 170 pounds per square foot on the snow, or about the equivalent of an average man on snow-shoes. It will operate on bare ground if necessary. Operating the Sno-Motor is a job that takes skill.

Sno-Motor trolley

Softly and silently fell the snow, and when the air finally cleared after the February 18-23 storm, there was a covering 70 inches deep at Florence Lake, 97 inches at Huntington Lake, and 77 inches at Shaver Lake. The town of Big Creek received 38 inches, while only three miles away (but 2,000 feet lower.) Big Creek No. 2-2A received only three inches.

The highway was blocked by snow, as was the Edison road down the canyon to power-houses Nos. 2-2A, 8, and 3. During the several days that the State Highway Department's snow-plow was broken down, the Edison Sno-Motor was the only means of transportation in the area. It made several trips down the Camp 7 hill to No. 2-2A, and one to Shaver Lake. Residents of the Big Creek Region were snowed in for five days.

NOTES ON THE OPERATION OF POWER-DRIVEN CONVEYANCE FOR SNOW: MOTOR-TOBOGGAN

James C. Marr

A motor-toboggan was purchased jointly by Division of Irrigation, Soil Conservation Service, and Boise River Board of Control in January 1942 for travel into the mountains of the Boise River Watershed of Idaho to make snow-surveys. The cost of this toboggan, delivered at Boise, Idaho, was $657.54.

The motor-toboggan has been used during three winters with varying degrees of success, depending upon condition of the snow and terrain. When the snow has been reasonably firm and cold, in condition that may be considered good for skiing, the toboggan has operated satisfactorily. A road or other uniform surface with minimum side slope and grade not to exceed 15 per cent is essential if satisfactory progress with the machine is to be made.

Many difficulties have been experienced while operating this machine when conditions have been unfavorable. If the snow is sticky the power necessary to make the toboggan slide is increased greatly and usually the machine either will not move or must travel in low gear. The engine heats quickly during low-gear driving and soon freezes up if not stopped frequently. This snow-condition usually occurs in the spring after April 1 and during afternoons. It may be avoided at times by traveling early in the morning and after dark when the temperature is lower.

Over-ripe snow has much the same effect as sticky snow. It offers less friction but affords insufficient traction for the toboggan to operate otherwise than in low gear. Very moderate side slope will cause the motor-toboggan either to slide sideways or to turn over. Upon three occasions during its use on Boise River Watershed it has rolled over and pinned drivers beneath it.

The upkeep has been large. So far not more than 250 miles of travel have been performed and it has been necessary to replace its runners three times, besides making many repairs and adjustments.

The Game Department of the State of Idaho has three of these machines in operation. They were purchased last winter. Two of them were put in operation in the vicinity of Boise, Idaho, and before the winter was over both were laid up for extensive repairs. The third was put to use in the Upper Snake River country near Yellowstone Park where temperatures are lower and the snow presumably more suitable for the operation of these machines. According to last reports this latter machine has given satisfaction, due no doubt to the different snow-condition.

While the experience with this motor-toboggan in the Boise Watershed Area does not justify its recommendation for use elsewhere for snow-surveying, it is the consensus of opinion that sufficient use has been and will be made of it to justify its acquisition. From a research standpoint, study of its principles of operation under the various snow-conditions has been worth while.

U. S. Department of Agriculture,
Soil Conservation Service,
Boise, Idaho

ADDENDUM--SNOW-SURVEY SYSTEM, BRITISH COLUMBIA

S. H. Frame

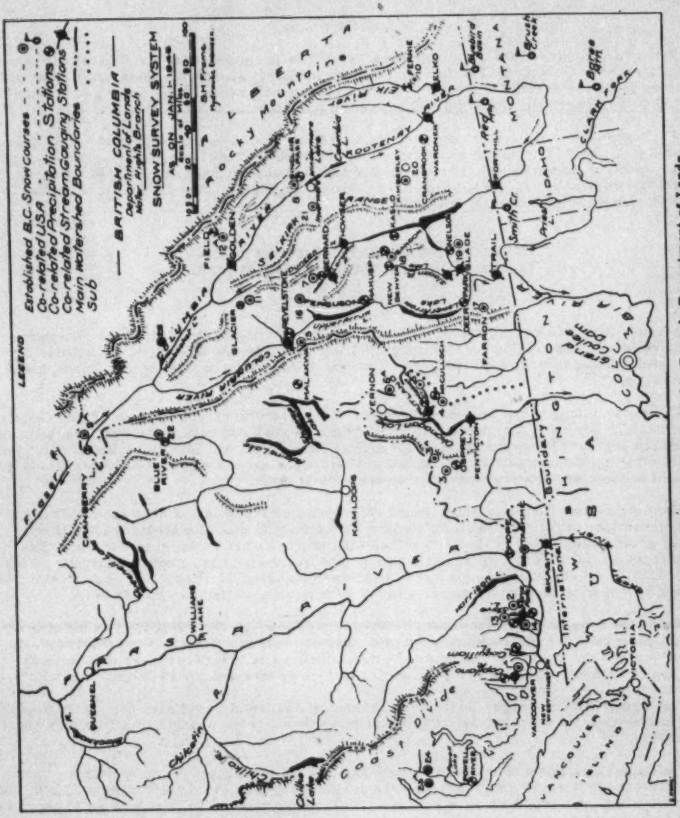

Fig. 1--Snow-Survey System, Water Rights Branch, Department of Lands, British Columbia, January 1, 1945 (see pp. 105 to 107)

Department of Lands, Water Rights Branch,
Victoria, B. C.

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National Research Council

AMERICAN GEOPHYSICAL UNION

TRANSACTIONS OF 1944

TWENTY-FIFTH ANNUAL MEETING
JUNE 1, 2, AND 3, 1944
WASHINGTON, D. C.

PART II

REPORTS AND PAPERS

GENERAL ASSEMBLY,
SECTION OF GEODESY,
SECTION OF SEISMOLOGY, AND
EASTERN SECTION OF SEISMOLOGICAL
SOCIETY OF AMERICA,
AND MINUTES OF MEETINGS

Published by National Research Council
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November, 1944

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INTRODUCTION

TWENTY-FIFTH ANNUAL MEETING
PARTS II TO VI, TRANSACTIONS OF 1944

The American Geophysical Union was established in 1919 as the American Committee of the International Union of Geodesy and Geophysics, and its Executive Committee is the Committee on Geophysics of the National Research Council. The objects of the Union are to promote the study of problems concerned with the figure and physics of the Earth, to initiate and coordinate researches which depend upon international and national cooperation, and to provide for their scientific discussion and publication. In the accomplishment of these objects, the Union is divided into Sections following the plan of organization of the International Union of Geodesy and Geophysics. There are now eight Sections, namely, (a) Geodesy, (b) Seismology, (c) Meteorology, (d) Terrestrial Magnetism and Electricity, (e) Oceanography, (f) Volcanology, (g) Hydrology, and (h) Tectonophysics. A Section of Geophysical Chemistry was discontinued May 31, 1924, as the International Union had failed to provide such a Section. The Section of Hydrology was established November 15, 1930--matters pertaining to scientific hydrology referred to the American Geophysical Union had been previously looked after by special committees on Hydrology. The Section of Tectonophysics was established April 9, 1940, for the purpose of promoting and encouraging research of fundamental importance to our knowledge of Earth-structure not covered in any one of the other Sections of the Union.

Annual assemblies of the Union and annual meetings of its Sections for the discussion of reports and for symposia are held each year. The first 13 assemblies and meetings--those in each of the years from 1920 to 1932--were held in Washington, D. C. Besides the annual general assemblies and meetings of each of the Sections held since 1933 in Washington, D. C., regional meetings of Sections were held at Berkeley, California (1933 and 1934), at Pasadena, California (1938), at Denver, Colorado (1937), at Spokane, Washington (1937), at Davis, California (1938), at Los Angeles, California (1938), at Spokane, Washington (1938), at Richmond, Virginia (1938), at Columbus, Ohio (1939), at Stanford University, California (1940), at Seattle, Washington (1940), at Sacramento, California (1941), at Dallas, Texas (1941), at Pasadena, California (1942), at Corvallis, Oregon (1943), and at Berkeley, California (1944). The transactions of annual assemblies and meetings through the ninth were published in the Bulletin series of the National Research Council as follows: Second, 1921, No. 17; fourth, 1923, No. 41; sixth, 1925, No. 53; seventh, 1926, No. 56; eighth, 1927, No. 61; and ninth, 1928, No. 68. Transactions of the tenth and eleventh annual meetings held in 1929 and 1930 were published in one volume in June 1930, and those of the twelfth, thirteenth, fourteenth, fifteenth, sixteenth, seventeenth, eighteenth, nineteenth, twentieth, twenty-first, twenty-second, twenty-third, and twenty-fourth annual meetings were published in June 1931, June 1932, June 1933, June 1934, August 1935, July 1936, July 1937, August 1938, July and August 1939, July and September 1940, July and August 1941, August and November 1942, and September and November 1943, respectively, as Miscellaneous Publications of the National Research Council. The Transactions of 1944 (Parts II to VI), also a Miscellaneous Publication of the Council, includes the proceedings of the twenty-fifth annual meetings at Washington, D. C., in the Hall of Government of the George Washington University, June 1, 2, and 3, 1944; Part I contains the proceedings of the joint regional meeting of the Section of Hydrology and the Western Snow-Conference at Berkeley, California, February 17 and 18, 1944. At the first, third, and fifth annual meetings in 1920, 1922, and 1924, respectively, there were no scientific papers presented; therefore, the transactions for these were not printed but were mimeographed for limited distribution only.

Parts II to VI of the Transactions of 1944 present 128 papers and reports, with discussions, communicated at the twenty-fifth annual meetings in 1944, as well as papers communicated after that meeting. As in the Transactions of 1943, the minutes of the Washington meetings, with their appendices, are published (Part II, 1944). The total attendance of members and guests at the twenty-fifth annual meetings, despite the urgent demands upon all because of the war, was in excess of that registered, namely, 496.

Eight resolutions were adopted. The subjects of these are as follows: Postwar work in geophysics; proposed oceanographic work by the United States Hydrographic Office; establishment of a geophysical station at the University of Alaska; investigation of microseismic phenomena; accurate time-service; thanks to Major Peter W. Rainier (for his presentation of the effective work done by him in supplying water-supplies for the British Eighth Army in the North African Campaign); and thanks to George Washington University (for facilities extended for meeting).

The sixth award of the William Bowie Medal to HENRY BRYANT BIGELOW was made at the evening General Assembly, June 1, 1944, immediately following the address of retiring President

W. C. LOWDERMILK. The general meeting, on the afternoon of June 2, 1944, was devoted to consideration of resolutions, reports of Union Committees, and discussion of plans looking toward rehabilitation after the war of the International Union of Geodesy and Geophysics.

The volumes of Transactions of 1944, by reason of the Special Fund attained by June, 1944, and so generously given by members and friends of the Union and by the Rockefeller Foundation, initiate the evolution of the Transactions as a journal devoted to scientific geophysics. It is planned that, besides papers presented at called meetings, communicated papers and items of interest to geophysics will appear bimonthly.

The General Secretary edited the manuscripts for publication after preliminary editing by the secretaries of Sections. The cost of publication was met through allotment by the National Research Council and annual dues of members. As in past years, the Union is grateful for quarters provided without cost by the Carnegie Institution of Washington at its Department of Terrestrial Magnetism. Each of the authors, except for a few who can not be reached, revises a carbon of the master-copy from which the Transactions are printed by the offset method. The final master-copy is prepared by J. J. CAPELLO, Mrs. ELEANOR M. LANIGAN, and W. E. SCOTT, and printing is by the Kirby Lithographic Company of Washington, D. C. Preparation of drawings and frequent necessary recasting of authors' illustrations are done by W. C. HENDRIX, and the large amount of photographic work required by J. W. GREEN.

The American Geophysical Union has made every endeavor in the past year to increase the coordination and collaboration of interests, especially with the geophysicists of the Western Hemisphere and to maintain a considerable part of the continuity of the functions of the International Union of Geodesy and Geophysics, thus protecting for the future those international relations so essential to geophysical research.

The Union attained its twenty-fifth year in 1944. In the quarter-century it has done much to advance geophysics--nationally and internationally--not only as a first-order science but as the foundation of economic applications which will be increasingly valuable in the postwar period. The realization in 1944 of special funds to permit enlargement of activities is a good omen for future service.

J. A. FLEMING, General Secretary,
American Geophysical Union

AMERICAN GEOPHYSICAL UNION

TWENTY-FIFTH ANNUAL MEETING

EVENING GENERAL ASSEMBLY

PRESIDENTIAL ADDRESS
AWARD OF WILLIAM BOWIE MEDAL

Washington, D. C.
June 2, 1944

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EVENING GENERAL ASSEMBLY
JUNE 2, 1944

PRESIDENTIAL ADDRESS

DOWN TO EARTH

Walter C. Lowdermilk

For seventy centuries of civilization, which is man's own show and venture into the unknown, mankind has sought a more abundant life on this planet, but with more of failure than of success. This holocaust of war leads to the conclusion that civilization has been weighed in the balance and found wanting. Now we are fighting to the death for another chance. It is not my purpose to discuss the abstract motives of good and evil that may inspire man's actions, but, rather, to bring our thinking down to Earth.

For more than 20 years my profession has been to read the records which farmers, nations, and civilizations have written in the land. My chief interest in these studies in land use is to find the basis for a lasting adjustment of human populations to the Earth.

These travels have taken me across six of the seven seas to study land use in 26 countries in four continents. I have also had a bird's-eye view of 11 other countries in aerial flights to and from China. Surveys of land use have taken me into those regions where civilizations first arose in the Near East and in the Far East.

What do we find? The cradles of civilizations are in decline; ruins of great works bespeak former wealth and splendor amidst modern decadence and poverty. Evolution of civilization appears to have gone in reverse. For it is chiefly in the newer lands, occupied in comparatively recent times, that people enjoy a greater abundance. This is an arresting tragedy. As I have looked upon ruins of old lands and depressing poverty and backwardness of their peoples, I was deeply moved by the wastefulness and ineffable sadness of man's failure to adjust himself to the bountifulness of the good Earth.

In ignorance and wastefulness, mankind has strode across the face of the Earth for 7,000 years reaping where he has not planted and destroying what he has not made. In occupying new lands man skimmed off the "cream" and left "thin milk" for the generations to come. Man tends to destroy the source of his existence.

The children of men found the Earth literally a "Garden of Eden." But after 7,000 years of increasing command of tools and machines, civilization is on trial for its wastefulness of land. Thus far, we have no guarantee that civilization will long endure. On the basis of past performance, the prospect for the future is that mankind will mine out the Earth's resources and productivity from place to place, leaving desolation as of abandoned mines of our west, until the habitable parts of the Earth have been exploited and laid waste. Suicide of civilization seems to be the end of this march of ruthless exploitation, rather than a more abundant life for people.

If civilization is to endure, society must be born again out of an economy of exploitation into an economy of conservation. "Where there is no vision the people perish!"

Though past failures are more common than successes, there is yet hope and yet time, as we appraise the possibilities of this old Earth in its stored resources and regenerative powers derived from the energy of the Sun. If we find the facts and understand and make full use of energies and forces that stand at our service on every side, we may still have a more abundant life for all people.

We have in the will to survive, motive power enough to make civilization a success if the means are known and understood. I shall leave to others the discussion of how motive powers of a people may be stimulated and directed, and confine myself to an examination of certain geophysical controls that condition any type of civilization whatever its motivation. The law of gravitation is not subject to a decree of the court nor is the force of running water modified by popular vote. "They build the house in vain except the Lord build it" was said by a seer of long ago. We build a civilization in vain unless it is backed by the laws of the universe.

First it is well to take stock of this planet as a dwelling place of mankind, as well as man's stewardship of it. After all, man is a newcomer and sojourner. The Earth was already old in a display of manifold phenomena of terrestrial forces before the first hunter and the first farmer

Fig. 1--Volcanologists are supplied with more and new data on volcanoes in the eruption of Parícutin in Mexico in August 1943--a reminder of the "ring of fire" around the Pacific (Courtesy Science Service)

ever sought out food for his family and himself. The sea was filled with waters; rains descended and floods came and went; continents were uplifted and worn away again and again by geologic erosion of streams and winds; and the debris was sorted and spread out in great sedimentary deposits and compressed into rock-strata; countless volcanoes had burst forth in landscapes where there was no man to see or to hear; lava had poured forth in great fiery lakes without a human spectator. The sea advanced and receded. Vegetation in many forms had spread over land in mild and moist climates, and under its protection, fertile soils were formed; beasts of the field, birds of the air, and fishes of the deep evolved, flourished, and by some failure of adjustment to environment became extinct. Whether or how soon man also may go the way of the dinosaur or project himself into the distant future, will depend on how well he works out adjustments of civilization to the good Earth.

The Earth is the silent partner in the rise and fall of peoples and civilizations. It richly rewards the diligent and understanding. It brings a curse of poverty and decadence upon those who

Fig. 2--In the silence of death stand excavated ruins of a former prosperous and beautiful ancient Roman city, Timgad, of Algeria, North Africa. Change of climate since Roman times is not the cause of this desolation, but misuse of the good earth.

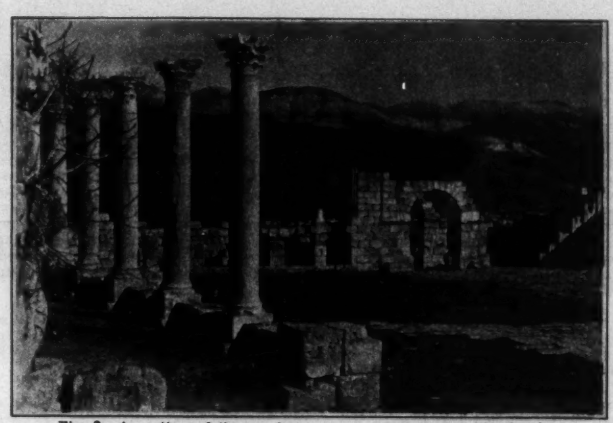

Fig. 3--A portion of the market square of Cuicul, long dead and buried, as disclosed by archaeological excavations. Now slopes once covered with olive orchards and vineyards are grazed into the ground and are eroding more and more. Such is a monument to misuse of land rather than to adverse change of climate.

Fig. 4--Normal sculpturing of a landscape may be accelerated by clearing off the natural protecting cover of vegetation, as has been done by heavy and overgrazing in this Idaho landscape. Bare land absorbs downpour of rain less rapidly than before; surficial runoff is increased. Flashy storm-flows cut deeper than before the valley-floors into gullies and arroyos. Lowered base-levels further increase runoff-velocities, cutting and carrying power of storm-runoff in geometric ratios. Erosion of this landscape is accelerated above the geologic norm of erosion of the area with consequences unfavorable to human welfare.

neglect and waste its substance. An ancient Law Giver said, "The sins of the father shall be visited upon the children to the third and fourth generations." But in the wastage of the Earth's resources, sins of exploitation and wastage are visited upon the children for ten times three and four generations to come.

For, in the last reckoning, all things are purchased with food. Such is the fateful and awful truth that hideous famines make known. World-wide war, that today is strangling civilization, also shows up the enormity of this fact. People sell their liberty, their all for food when driven to extremes of this tragic choice. When food fails, all else fails--civilization falls apart. There is no substitute for food.

Moreover, our civilization is bought with food, our cultural advantages and satisfactions, our advance in science, our industrial achievements as a Nation, and now our war effort. Food, abundant and adequate, is necessary for victory. The flag is on the plow as well as on the battleship and on the factory. This partnership of land and farmer is the rock foundation of our complex social structure, which provides high standards of living, cultural, and recreational facilities.

Fig. 5--A long story is recorded in this aerial view of the Piedmont, South Carolina. Before clearing and cultivation, this area was covered with dense climax forests of oak and hickory. But all this area has been cleared and cultivated. Under 40 inches of rainfall soils on rolling fields eroded until crop-yields no longer would justify costs of labor and seed. Such fields were abandoned and grew up first to broom-sedge, into which volunteer seedlings of pine came. In time, pine-stands grew on abandoned farm fields. All these stages may be seen in this fascinating view from the air.

"Man shall not live by bread alone." But he must have bread to live and to take part in other advantages.

It was in Egypt while contemplating the Pyramids and long use of land in the Nile Valley that I grasped more fully the basic relations of civilization to the land. About 6,000 years ago, a genius of a farmer hitched an ox to a hoe and invented the plow, and for the first time applied power in agriculture. This made the farmer more efficient in growing food. More than he needed for his family and himself released some of his fellows for other tasks. Greater farmer efficiency led to divisions of labor that gave rise in time to a complex civilization of higher standards of living. As I imagined unrest of unemployment brought on by this first increase in farmer efficiency, I suspected that the great pyramids of Egypt were the first great Work Projects Administration projects.

Maximum production is the goal. Land is the silent partner of tillers of soil in this exacting and vital task. But the land may be damaged or destroyed by wasteful cultivation and misuse. We have examples in the new land of America, where in a comparatively short period of occupation in the United States alone an area larger than Kansas has been ruined for further cultivation and now fully 200 million acres are eroding faster than soil is being formed. The present National soil-conservation program, which farmers of more than three-fourths of the total farm-area of the

Nation have joined in soil-conservation districts, has only made a beginning in this great task. This is the first time in human history that a Nation as a whole has taken thought and action to combat this evil of civilization that destroys productivity of lands as need of them grows.

The world is today more fully occupied and populated by the human race than ever before. All lands have been possessed by nations. No free land remains. Mankind is left to work out its salvation on lands now occupied. Of the total area of the Earth, about 3,054 million acres are reported under cultivation and support the present world population of about two billion souls. On the average, 1.5 acres grow the crops for one person. This population is increasing rapidly. Since 1800 the world population has increased from 604 million to 2,000 million, or threefold in about 150 years. All land suitable for cultivation is estimated at about 3,714 million acres, or one-tenth of total land-area. Most of the unbroken area of possible cultivation lies in the tropics with its serious drawbacks. All the best land in the most habitable parts of the world is already under cultivation. A vast area has been ruined for further cultivation and much of it is being depleted by misuse and soil-erosion that lessens prospects of the food supply in the face of an enlarging population with its increasing demands.

In the face of the limited area now available to the human race, the idea that man is still destroying its usefulness by inconsiderate and wasteful methods should shock all thinking people into action. If man is making deserts out of productive lands it is a matter not only of National but of world-wide concern. It is an international tragedy. If a Nation would project itself into the future, it must protect its lands from the ravages of soil-erosion. When lands are impoverished, peoples lower their standards and suffer privations both physically and spiritually. Soil-erosion is a deficiency-disease of the land which begets deficiency of food, vitality, and higher values for peoples and nations.

Land, therefore, is not an economic commodity but an integral part of a Nation, even as its people are. Man expresses his moral obligation to posterity as surely through the Earth as through his social institutions. Fertile or sterile lands that are passed on to feed future generations are, apart from blood descendants, our most direct link with the future. When the Earth's resources are wholly husbanded in the advanced knowledge of full conservation, the possibilities of the Earth for increased populations are far beyond the imagination of mankind in general. If the vast energies of the human race and resources of the Earth could be directed toward a goal of conservation instead of destruction and despoliation, the good Earth would respond with abundance for all.

Only by conservation in the fullest sense, of the basic resources of land, water, and the spirit of peoples, can we maintain the human values of wholesome standards of living, opportunity, freedom, justice, and faith in the destiny of our civilization. Only in conservation have we the assurance of continued progress in the search for that something which has led humanity out of the stone age into an industrial age in which powered machinery increases efficiency of all divisions of labor. Only by conservation can we be led on to a higher economic, physical, and spiritual development which expresses itself in stewardship of the Earth for the well-being of the individual, the State, and the survival of civilization.

This working out of a lasting adjustment of people to the Earth calls for the application of a wide range of earth-sciences as well as biological. The need to provide for the enlarging technology of today calls for more and more facts about the Earth and the universe.

Such is the province of the American Geophysical Union. The American Geophysical Union is commissioned to "promote the study of problems of the figure and physics of the Earth, to initiate and coordinate researches on natural phenomena of earth-processes and interpretations and applications to human welfare." Such action depends on National and International cooperation and scientific discussion and publication. These duties are organized under eight sections of the Union: Oceanography, Terrestrial Magnetism and Electricity, Seismology, Volcanology, Tectonophysics, Meteorology, Geodesy, and Hydrology. These embrace fields of knowledge of physical phenomena necessary to the working out of a lasting adjustment of mankind to the Earth. Not only is this knowledge of immediate use in supplying material needs but is of highest value to satisfactions and noble pleasures of mind and spirit in understanding and contemplation of the wonders of the Earth and of the universe.

In the course of my travels, I have seen many of these great earth-forces in action and their effects. This evening, I wish to share with you some of these experiences in seeing wonders that are sufficient to excite scientific curiosity for centuries to come. Especially was this true on my recent trip to China and return, in which I sailed the seas for 60 days and flew the full length and breadth of Africa and across India into China.

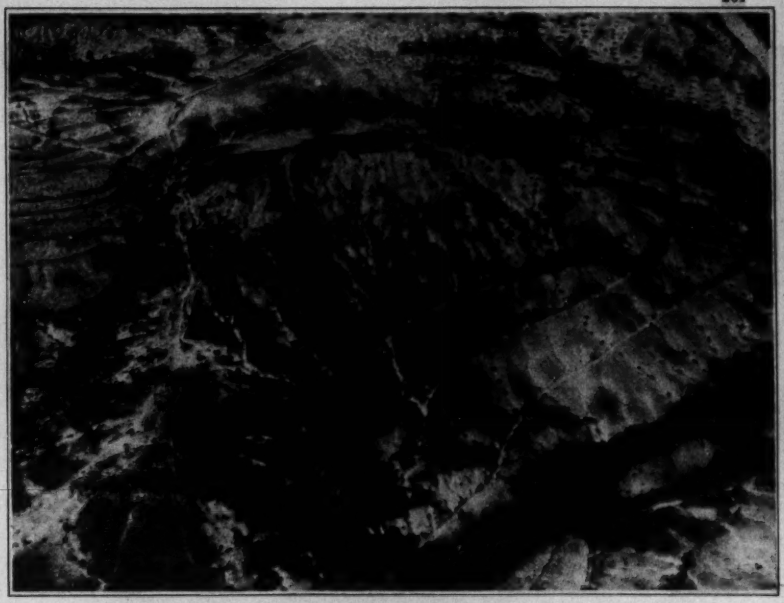

Fig. 6--From the air, one sees how, near Dadeville, Alabama, rolling lands of the Piedmont have suffered serious damage from unwise use of land. Hundreds of new drainage-channels show how unabsorbed waters from heavy rains are washing away soil and guttering hillsides to change the regime of waters and to lower capacity of the land to grow crops.

Fig. 7--Down to Earth in the fair land of America. Misuse of the good earth here has destroyed land for any further cultivation and calls for costly measures of restoration to crops of lesser value in trees. Such misuse of land will not long support a prosperous civilization.

Fig. 8--Dynamics of land-shaping processes in action! In the hydrologic cycle, the circulation of water in rain-runoff and stream-flow has been the major agent in sculpturing landscapes and in generating crustal movements by accumulations of the products of erosion in vast sedimentary deposits. Here clearing land of its original protective cover of vegetation for field-crops has accelerated processes of earth-sculpture to rates that undermine the welfare of farmer, community, and Nation, and, indeed, of civilization, and calls for measures of land-use that hold in leash the dynamic action of geophysical processes.

This and former sailings give me a high respect for the science of oceanography. Of all the deserts I have traveled, the ocean is the most lonely and desolate, merciless, and majestic. Its restless currents, winds, and waves have played a vital part in the evolution of civilization, and will continue to do so. The ocean was particularly forced upon me on my trip to China in 1942, when military considerations required our ship to change its course to go through the Panama Canal, which sailors call the big "ditch," and down the full length of South America and around the Horn through Antarctic waters and south of the Falkland Islands to South Africa. For 45 days we saw no land except for a glimpse of Cape Horn. How immense, how vast are the waters of the ocean!

We passed through the Caribbean Sea, where are brewed the hurricanes that sweep the South Atlantic States. A wonderful display of cumulous clouds was boiling up from a steaming sea into a vast dome, beneath which the visible sea was like a bowl filled to the brim. The circle of the horizon moved with our ship as WILL ROGERS' spinning loop used to follow him across the stage.

As we crossed the equator off Ecuador, the weather suddenly changed from steaming heat to chilly winds that forced us into warmer clothing. The Peruvian Current from the Antarctic brought cold waters to the tropics off South America. We left behind the Dipper, and under the

spell of the Southern Cross we entered the "Roaring forties," so called by sailors of the Seven Seas. Our ship rolled and pitched on waves like moving hills that bore down on us and burst into plumes of spray that scattered before the wind like dust over the sea. After the first storm, I wrote my wife that I knew I had thrown up everything but my appointment to China. After that, in other storms I was a fascinated onlooker from the bridge.

The ocean in a storm is an awesome thing. Our little ship, though loaded heavily with bombs, bobbed and tipped far to the right and the left like a log as great masses of writhing monstrous waves struck her time and time again. So has the sea tossed up its angry arms for millions of years, but little comes of it until waves strike the land and wear it away.

Life above that southern sea amazed me. The albatrosses, great bomber-like birds, adopted our ship and wheeled in great figure eights about the ship day after day. Cape Horn pigeons also followed after. They are the most perfect flying machines I have ever seen. Their mastery of turbulent air-currents was a daily source of wonder and admiration and should be studied with slow-motion moving pictures.

The ocean, which covers 70.8 per cent of the Earth's surface, with its life, its mineral salts of prodigious quantities, its storms and winds, its currents bringing warmth to cold areas or cooling winds to hot lands, calls for full play of scientific imagination and profound investigations fully to understand its mysteries and to make use of garnered facts for the benefit of mankind in his search for security in an abundant life.

Flying along the east coast of Africa to Mombasa, thence overland to Lake Victoria and down the full length of the Nile to Cairo and on, gave me a bird's-eye view of evidences of many past and present workings of Earth forces.

As we neared Mombasa on the coast, our pilot maneuvered the giant flying-boat to avoid a thunder-storm that filled the sky in the west. Vivid flashes of lightning illuminated the vast boiling storm-cloud. It was a grand sight. Natural electricity was being generated to enormous voltages. Here was a majestic show of earth-electricity that has in lightning and its thunder struck awe in the minds of man for unknown ages. After so long a time we are only beginning to gather facts for understanding these phenomena, such as the accumulation of electrical static charges within clouds.

This spectacle suggested the field of Terrestrial Magnetism and Electricity, which is the study of magnetic and electrical phenomena of the Earth's interior, surface, and atmosphere. The Earth is like a great armature spinning in space, generating a magnetic field, to which man is insensible. But instruments are now so perfected as to make use of these forces for many purposes, some of which are well guarded military secrets.

Recent developments advance our knowledge of cosmic radiation and relations of electrical and magnetic conditions to solar phenomena. Radio communication is advanced by results of researches in this phase of earth-forces. Location of geological structures and ore-deposits is also facilitated by magnetic studies. In the larger problem of adjusting civilization to the Earth, the field of terrestrial magnetism and electricity contributes to efficiency in communication and information of the people as was little dreamed of in the past. It serves to make the whole world a neighborhood.

I have seen many evidences of faulting of the Earth's crust that set up earth-waves as studied in the field of seismology. Flying from South Africa to Suez, just east of Lake Victoria on the equator, I had a bird's-eye view of the great Gregory Rift, which is a part of the much-faulted region of Central Africa. This earth-fracture reached from horizon to horizon to the north and south. The land to the west had dropped down 3,000 feet or more, leaving a great cliff standing, bold and naked. At its base were great blocks of the Earth's crust all awry, with edges fresh and scarcely weathered, as if this great rift took place only a few months ago. The Earth's forces had a field-day here. This escarpment is in the roof of Africa that seems to have fallen in over a great area and may be related to the great Jordan Valley Rift to the north.

Our great hydroplane dropped down on the smooth surface of Lake Victoria in a sunny calm and cool evening. The lake reflected the western Sun on a vast surface bounded by indented shoreline and broken by many islands along the shore. Victoria on the equator lies at four thousand odd feet elevation and is the largest of a group of five great lakes that owe their origin to the rift-faults in the roof of Africa. Here also the four great rivers of Africa have their source: To the north, the great Nile; to the east, the Ruaha; to the south, the Zambesi, that then turns east into the

Indian Ocean; and to the west, the great Congo. Lake Victoria has an area of 26,800 square miles--between that of Lake Michigan and Lake Superior. Vegetation about Lake Victoria was luxuriant, showing ample rainfall. Much of the lowlands was cleared and cultivated to small farms, exposing bright red soils. But sloping fields showed tell-tale gullies of soil-erosion on the equator.

In the rosy dawn of the next day, the mighty engines pulled us off the glassy surface of Lake Victoria, and our pilot turned to the northward. But on the way he gave us a great show by flying very low over the Uganda Game Reserve, where the roar of our motors flightened many herds of wild elephants--in all 96 according to my tally. Next he flew us from Lake Albert up the Victoria Nile, with its hundreds of hippopotamuses, too many to tally, and then over the beautiful Murchison Falls. Thence we turned due north over the great marshy region of the White Nile and on over vast brown expanse of the Sudan. Waters of the Upper Nile were running clear. The drainage-area is well clothed with vegetation.

We stopped for the night at Khartoum, an ancient and strategic location, where the Blue Nile, draining igneous rock mountains of Abyssinia, joins the White Nile. From Khartoum to Cairo the following day we passed in our flying boat over the driest desert I have ever seen. For hundreds of miles I could not make out a bush, or evidence of any living thing except in the entrenched alluvial valley of the Nile as we crossed it. The landscape was naked, showing erosion in the raw; it was more like the surface of the Moon than anything else. Here, indeed, is a region of high interest to climatologists, for it represents an end-point of the range of climatic controls.

The landscape was worn down to near level, a peneplain in which a new cycle of erosion had only recently begun, in geologic time, cutting to a new base-level 100 to 300 feet below the former level, which may well date back to Pleistocene times. Sand-dunes in beautiful crescents spread wide over parts of the landscape. Blackish wind-swept areas with sand-filled drainage-channels made a fantastic sight. Here wind, heat, and cold held full sway.

In this vast lifeless desert flows the great Nile in a comparatively narrow entrenched flood-plain of rich well-watered alluvium. These fertile lands teem with crops and villages. As I looked down upon this fascinating scene from far above, methought how man with all his boasting is a child of the Earth, dependent on favorable combination of natural materials and forces.

The best known and most remarkable rift or trough-fault in the world is that of the Jordan Valley. A narrow strip of the Earth's crust from the mountains of Turkey southward to the Gulf of Aqaba of the Red Sea is faulted down like a trough. The deepest part is in the Dead Sea depression, where the rift valley-floor has slipped down from the high rim of Trans-Jordania over 7,500 feet and to 2,600 feet below sea-level. This depression is partly filled with brine of the Dead Sea up to a level still 1,300 feet below sea-level. The Dead Sea acts as a great evaporation-pan lying in a furnace-like valley from which water to a depth of 7 to 17 feet is evaporated each year. In a survey flight in 1939 over this unique region, I saw from the plane the physical relief of the Holy Land all laid out below me--Highlands of Mt. Hermon to the north, the Sea of Galilee, and Jordan Valley as a great trench leading to the Dead Sea deeply sunk below sea-level, and the Mediterranean shores to the west only 25 miles from this great gash in the Earth. Here natural forces had combined to set the stage for a great irrigation-and-power project, to coordinate full possibilities of all physical features and natural forces on the order of the Tennessee Valley Authority. I have proposed this Jordan Valley Authority as a means of putting natural features of this unique region to full use, to take out all sweet waters of the Jordan River for irrigation of more than a half million acres of dry lands, and to lead in Mediterranean salt-water through a canal and tunnel into the rift-valley to develop hydroelectric power up to one billion kilowatt-hours per annum for industry. The sea-waters are to be exhausted in the Dead Sea and evaporated. The salt sea-water will only add to the rich store of minerals in the Dead Sea, such as magnesium, potassium, bromine, and salt. By raising the level of the Dead Sea nearly a hundred feet, evaporation-surface is increased 20 per cent to 260,000 acres. From present incomplete measurements, annual evaporation is tentatively accepted at ten feet. That would permit the bringing in of about 2,600,000 acre-feet of sea-water per year for generating electrical power through a fall of 1,200 feet.

Such a project is a concrete example of how a full coordinated use of raw materials and natural features and forces of the Earth may contribute to the adjustment of mankind to this old Earth that is full of wonders to perform.

Earth-movements give rise to earthquakes round the world. In the great loess highlands of Northwest China, slippage of long slopes started by earthquakes buried thousands of people in their loess cave-homes in 1921. I examined a land-slip of a year ago that in an earthquake had pushed

across and dammed the Yellow River at Kong Ho. A village of 270 persons was buried without trace.

These terrifying earth-movements are beyond control but we can interpret them and sometimes anticipate them, and map the faults in the Earth's crust where more earth-movements are likely to take place and locate towns and design buildings to withstand earth-vibrations. The Imperial Hotel in Tokyo was designed by an American architect against earthquake-shocks and survived the great Tokyo earthquake of 1923 without damage.

The most remarkable seismographic charts I have ever seen are those caused by typhoons of the Pacific as recorded at the Zi-Ka-Wei Observatory near Shanghai. Father GHERZI showed me charts of crustal vibrations set up by typhoons moving toward the China Coast that were detected as far as 600 miles at sea. At that time Father GHERZI theorized thus: That pulsations within low-pressure centers of violent typhoons developed a pumping action in sea-water that was transmitted to the Earth's crust and were recorded on the micro-seismographs. As soon as centers of typhoons passed to the land, vibrations stopped, for possibly the land-surface was too rigid to be affected by barometric pulsations.

Seismology is concerned with the transmission of vibrations through the Earth that reveal structure and density-layers within the Earth. Geophysical explorations make use of these facts for locating mineral resources. Seismology will, moreover, play a still wider role in the future in locating and designing buildings and structures such as dams and engineering works.

Throughout this flight over Egypt, Palestine, and Syria, I had a bird's-eye view of many dead volcanoes that bespeak much volcanic activity in the past. Volcanology is a science of the study of volcanic and intrusive rocks, the relation of ore-deposits to igneous activity, and description and classification of volcanoes. A volcanic eruption still is the ideal news-story; it is dramatic, tragic in part, and beneficent in part. Volcanic ashes may obliterate a city as I saw in the excavations of Pompeii, but in time they make such fertile soils that farmers push cultivation into danger-zones of possible eruptions as on the slopes of Vesuvius.

We saw Stamboli at night, pouring a river of red and molten rock from the bowels of the Earth down the mountainside into the sea, causing a fog of steam so dense that our fog-horn sounded for two hours. On Christmas Day of 1938 we struggled up through deep snow to the top of Mt. Vesuvius, over 200 acres of the lava that had been disgorged only a few days before and to the coughing cone from whose base red-hot lava was pouring forth. This jagged mass of lava was still so hot that it burned off soles of our rubbers and dried out our clothes, wet with snow, in a few minutes. During a week, Vesuvius had built a new 350-foot cone as every few minutes the mountain rumbled and trembled and with a noisy belch tossed tons of rock into the air that finally rolled down the cone out toward us. Out of a fissure near the base of the cone, earth-pressures were squeezing a steady flow of tons of red-hot liquid rock from deep inside the Earth. The glowing menacing flow of lava was a hellish thing as it hissed and steamed toward us. The air was stifling with sulfureous fumes so that a member of our party remarked: "Vesuvius must not feel very good; it has terrible halitosis after having thrown up 200 acres of lava."

The recent eruption of Parícutin in Mexico (see Fig. 1), that started in a farm-field, has given the world a great show and quickened scientific curiosity. This volcano reminds us of the ring of fire around the Pacific. Such phenomena yield data of value in several fields.

The field of tectonophysics is the eighth section of the American Geophysical Union to be formed, to meet the need for coordinating data from seismographs, geological structure, and experimental pressures for solution of problems of earth-structure. Strange as it may seem, the laws of melting rock under great earth-pressures and the piercing of armor plate by high-velocity projectiles are enough alike to bring tectonophysics also into secret service for war.

The three fields of geodesy, meteorology, and hydrology include information of more direct application in the major task to work out a lasting adjustment of mankind to Earth's resources and natural forces.

Geodesy gives us the foundations for mapping: Large-scale triangulations; lines of precise leveling; and gravimetric determinations. From these data we get the base-maps and compute the size, shape, and features of the Earth. Aerial mapping is a recent development of highest importance in the use of these base-controls. Practically all projects for making use of land, waters, and resources of the Earth call for accurate maps. Geodesy serves these purposes directly and in many ways.

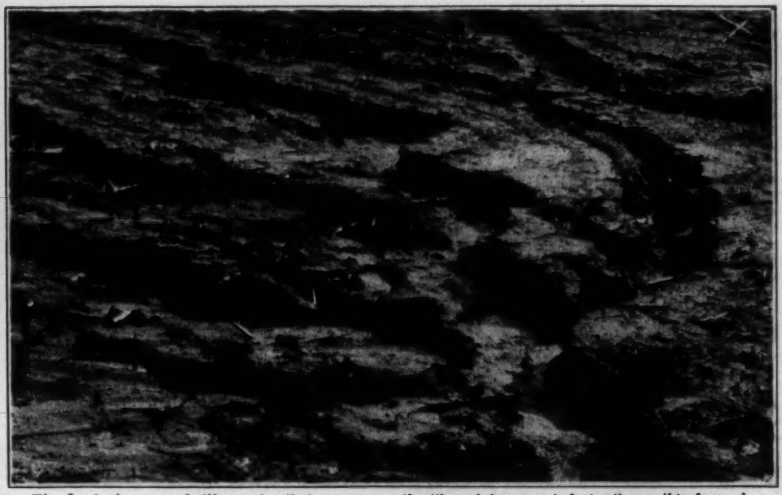

Fig. 9--A close-up of rill-erosion that removes soil with each heavy rain faster than soil is formed. This means destruction of soil unless erosion is controlled. The next plowing blots out such rills and removes tell-tale evidence of soil-wastage, for a time only. Rilling is followed by gullying that in time unfits fields for cultivation, to say nothing of depleting fertility of soil.

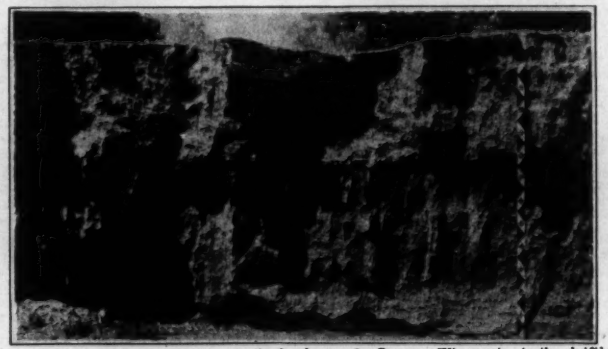

Fig. 10--A vital record is here written in the land near La Crosse, Wisconsin, in the driftless area that escaped glaciation during the Ice Age. But during the Pluvial period runoff from the drainage had cut a channel down to the depth here shown. After that, runoff lessened and filled the valley with alluvium of increasingly fine texture. Time was allowed for a distinct soil-profile to be formed as marked by the dark bank. Such was the state of things when clearing and cultivation of slopes began in the past century. With clearing of slopes, storm runoff eroded and brought down coarser material that was spread over the original alluvial valley-floor. Some five feet of this material accumulated until still another stage of runoff regime was brought about. For runoff seemed to have increased, or erodible material had been removed, to give storm-flow greater cutting power. For runoff from cultivated and eroding slopes was sufficient to cut through recent and ancient deposits down to the channel bed of glacial times.

In the past, few reservoirs had been accurately surveyed. In our program of soil-conservation we needed to know how much storage-capacities had been depleted by silting. We had difficulty in getting suitable information. It would be much better to have accurate capacity-surveys made of reservoirs before they filled. The Boulder Dam was soon to be completed. It would take years and great expense to make an accurate contour-map in that wild and rough country. Drop of the great gates of the Dam in 1934 began the filling of Lake Mead and shocked us into action. Arrangements were made with the United States Coast and Geodetic Survey to use their precise surveys of the reservoir-site as base-controls. In eight days aerial photographers made the flights and began making a map with a scale of 100 feet to the inch and ten-foot contours. Repeated flights were made as the water rose, photographing the rising water line at 20-foot intervals as measured at Boulder Dam. This was done to give checks on contouring the flatter areas of valley-floors. This map of the reservoir now filled with waters of Lake Mead will serve for silt-surveys in the future and will increase in value and use a century, two centuries, yes, a thousand years hence.

Geodetic gravity-readings give us data of highest theoretical value, but also serve the geologist seeking out mineral deposits. Gravity-readings and sonic soundings serve for mapping the floor of the ocean.

Planning for postwar work will call for a mapping program of unprecedented proportions to work out long-range uses of land, waters, and minerals of the Earth in the interests of human welfare. Especially is this true of China, whose people now are planning for a vast program of reconstruction. Geodesy will have an increasingly important place in earth-sciences.

Travel-lanes of the sea and highways of the sky have added to the needs of agriculture for greater knowledge of meteorology in forecasting of weather, storm, and flood. On my recent trip, our great hydroplane rose off the mysterious Nile at Cairo and wheeled over the sleeping city and took a northeasterly course over Sinai, Palestine, Lebanon, and the Syrian Steppe to Basra. Many students have ascribed the decline and decadence of this region to adverse change of climate. With the advantage of our bird's-eye view, we could make out ruins of former cities in a nearly empty land. Terraces of old had fallen down, soil-erosion had washed soils off the highlands to limestone bed-rock, leaving only dregs of the land in the narrow floors of valleys. These lands, bared of vegetation by ubiquitous goats, as I had studied them before, suggest lowered infiltration of rain, quick runoff, and reduced effectiveness of rainfall. Former ground-studies showed that reduction in effectiveness of rainfall was enough to account for decline of the country without adverse change of climate. For experiments reveal that misuse of land may reduce effectiveness of rainfall equivalent to an adverse change of climate.

My interest in this question goes back more than 20 years to North China. Decline of that vast land as seen in ruins of greater prosperity and larger populations of former times had been ascribed by RICHTHOFEN and HUNTINGTON and others to dessication as a result of adverse change in climate. But within the loessial regions in Shansi Province I found temple forests as green emeralds in a vast yellow gullied region. Within these temple forests vegetation was reproducing naturally without being planted or irrigated. Forest-litter covered soil-surfaces. Rains were being absorbed as they fell, for there was no evidence of runoff and no soil-erosion, whereas surrounding farm-lands were cut with great labyrinths of gullies. Soil-erosion from accelerated runoff on such a scale appeared to be enough to reduce productivity of the land without climatic change. Conditions within the temple forests indicated prevailing climate would support a complete cover of vegetation and control of soil-erosion. It was this finding that started me on a series of experiments to measure surficial runoff and erosion from land-surfaces under different uses. These experiments measured the effectiveness of rain. These and subsequent studies revealed that up to 50 per cent of heavy rain-storms may run off from bared sloping ground, whereas much less or no runoff comes from a similar slope covered with grass or forest and its litter.

Immediate runoff means loss of that much rain and gives the effect of dessication of a land. Before the theory of adverse change of climate is accepted it seemed well to discover in how far effectiveness of rainfall is changed by types of land-use--whether by unwise cultivation or by overgrazing.

At the ground-surface, meteorology and hydrology meet. The writer's studies on infiltration of rain and later studies by MUSGRAVE and others lead to the important conclusion that methods of land use influence the intake of rain by soils to decisive and critical amounts. Rates of infiltration are critical in land-use, in erosion-control, soil- and water-conservation, and in flood- and silt-control.

Success or failure of sustained uses of land and of man's adjustment to it--in fact, the destiny

Fig. 11--From the air is here seen the early stages of a man-made desert in the "Dust Bowl" of the Great Plains. These sand-dunes were created in ten years of misuse of the good and fertile earth of the Southern Great Plains. The process of destruction has been reversed and the dunes controlled and revegetated, a task much simpler than the control of less spectacular but more destructive water-erosion. An understanding of the characteristics of land and geophysical processes is required, wisely and safely to use the good earth.

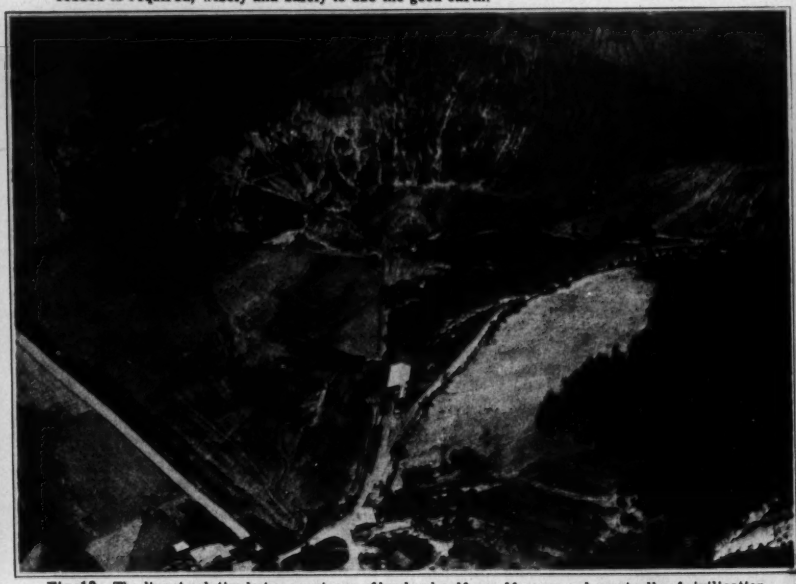

Fig. 12--The direct relation between misuse of land and welfare of farmer and eventually of civilization is apparent in this aerial view of a Georgia farm. Sustained and improved use of the good earth calls for the coordination of a number of technologies within the field of earth-sciences and geophysics.

of civilization--is determined far more than now realized by what happens to the rain-drop as it strikes soil-surfaces.

Moreover, a more complete understanding of climate and its variations, whether periodic or cyclic, will aid in adjusting agriculture and other uses of land to given regions. Especially is the study of microclimate coming into the forefront in agriculture and in making long-time use of forests and in reclamation of damaged lands.

Dynamic action of wind as it erodes rock and soil and carries sands and dust is a factor of high importance the world around. Wind-tunnels were first used for design of airplanes. Now portable wind-tunnels are used to measure wind-erosion of soils under different wind-velocities and under various measures for control of wind-erosion.

Sorting of soil in wind-erosion takes place, whereby particles of silt and clay are swept aloft to be blown to destinations unknown, and the coarser, sandy particles are left behind to form hummocks and sand-dunes. These "black blizzards", as we experienced them in the "Dust Bowl" of the Great Plains, have been known in lands long occupied in the Near East and in northwest China. A study of sand-dunes should give us a clearer understanding of past climates, possible climatic changes, as well as of formation of man-made deserts in marginal regions.

Factors of meteorology, including weather-forecasting and climatology, affect the destiny of human occupation of the Earth in many ways and decisively. In marginal zones, the effects of drier climates may be brought about by misuse of land- and water-resources. Full use of the land and waters calls for deeper understanding of all phases of this complicated science.

Hydrology is a synthesis of those subjects that have to do with the source, distribution, disposal, and work of waters on land. The ocean, as the mother of waters, is the source of rain. Its volume is almost 335 million cubic miles. Rivers run into the sea, yet the sea is not full. Waters of the ocean evaporate, are blown inland and rain down on the land, and their return in rivers to the sea makes up the hydrologic cycle. Rainfall on the land is computed at about 29,347 cubic miles, and runoff of rivers is about 6,524 cubic miles, or about 22.2 per cent of rainfall. Cold, dry air-masses take up moisture from land and carry it back over the sea to balance the equation of evaporation and precipitation. It would take 11,400 years for the volume of the ocean to be rained down on the land, and 51,280 years for the ocean to be filled by rivers running into the sea. Accumulation of ice-sheets might thus lower the level of the ocean quite rapidly in geologic time.

Properties and dynamics of rain-waters on the land are of fundamental interest in the economy of the Earth. Annual rainfall on the land (for rain at sea is not recorded) weighs about 123,259 billion tons, equivalent to the fabulous energy of 7,470,000 million horse-power. The compacting force of rain on bare soil is no small matter. Recent studies disclose remarkable effects of rain-drops as they strike bare soil on slopes.

Moreover, it is the circulation of this small part of the Earth's waters that has been the chief dynamic agency in moulding the face of the Earth and in setting up great stresses in its crust.

Running waters through the ages have excavated valleys, planed off the land to near level, transported erosional debris and spread it out in great sedimentary deposits, doing a prodigious amount of work. Cumulations of these deposits in time build up great overburdens, such as I saw from our hydroplane in the delta of the Zambezi River in East Africa, that disturb equilibria of the delicately balanced Earth's crust. These overburdens weigh down and slowly sink the crust into the underlying plastic magma to cause land-uplift elsewhere. These uplifts in turn set the stage for other cycles of erosion, sedimentation, and crustal movements. With these are associated faulting and possibly some volcanic activity. The dynamic action of rivers is far-reaching and decisive in the history of the Earth. Such is the mechanism whereby silent energy of rays of the Sun moulds the surface of the Earth.

It is this geologic erosion which has sculptured the land into forms of majestic beauty such as the Grand Canyon of the Colorado, fantastic Bryce Canyon, the little-known gorge of the Bramaputra, and thousands of lesser ones. Rivers and glaciers have wrought wonders. We have in these gigantic phenomena much more to call forth the exclamation that was sent as the first telegraphic message, "What hath God wrought."

Erosion of the land is such an universal phenomenon of running water that confusion sometimes arises as to the difference between this geologic erosion and the accelerated or man-induced erosion of cultivated fields or of hills from overgrazing or of bared land. The dynamics are the

Fig. 13--A beginning in applying principles of geophysics, engineering, and agronomy to conservation of land is shown in contour-farming and alternation of strip-crops, to increase intake of rain by cultivated soils and to reduce erosive action of unabsorbed rain-waters--Lancaster County, Pennsylvania.

same. But geologic erosion is as old as the first rain-storm; wind-erosion may be older. In those areas where favorable climate supports a complete cover of vegetation, a complex body of soil is formed under this protection. But geologic erosion goes on no faster than soil is formed. Soils form and differentiate into topsoil and subsoil on slopes, as valleys are excavated. Geologic erosion under such undisturbed conditions is a slow process in terms of a civilization.

But when this mantle of vegetation is cleared for cultivation, or for any other purpose and especially when the land lies on a slope, erosion of a new order comes in. Erosion is accelerated far beyond its normal geologic rates and much faster than soil is being formed and means destruction for human use unless controlled. This is the soil-erosion which must be adequately controlled if sustained production of land is to be maintained as an enduring basis for progress of civilization.

Dynamics of running water, when acting upon soils formerly protected by vegetation and especially on slopes, is a phase of hydrology of highest importance in working out a permanent agriculture to make sure a food-supply for peoples of the Earth. Lands must be so treated as to take in rain that falls on the land. In drier regions, loss of effective rainfall may be critical. Increased storm-runoff cuts and carries away the soil and means more silt in streams to add to problems of use of waters for power and irrigation and flood-control.

On my first trip to China more than 20 years ago, when still a day's journey from Shanghai

Fig. 14--A bit of the Earth's surface in Lancaster County, Pennsylvania, two miles northeast of Tayloria, as seen from the air, showing on the left how land is being depleted by unwise use and on the right how land is treated to conserve the fertile layer to maintain and to increase production of needful food-crops.

we entered a great broad band of brownish-yellow water, sharply contrasted against the blue-green waters of the ocean. Next morning my bath-tub water was heavy with silt. We were plowing through soils of China washed out into the sea by the Yangtse River.

Later, on an expedition into North China, I visited the site of the break in 1852 in the dykes of the Yellow River, when the great muddy stream changed its outlet from the Yellow Sea to the Gulf of Chihli 250 miles to the north. I climbed first the outer dyke and seven miles farther on the great inner dyke and looked upon a great brownish river full of shoals--the siltiest river on the Earth. This was "China's Sorrow" that was flowing some 30 feet above its delta-plain. For 600 years, millions of Chinese farmers had with bare hands raised the dykes year by year, over a distance of 400 miles to hold this giant river in its course, until it finally broke away.

Why should the Chinese farmers have to work so hard? It was because of silt, that each year partly filled the channel, making it necessary to raise the inner and outer dykes year after year, until finally the bottom of the channel had been lifted well above its plain.

I resolved to see the origin of this silt and went on another expedition into the loessial highlands. There we found the King River Irrigation-Project begun in 246 B.C., which had been put out of use time and time again because of silt. In the river-drainage I found a vast region cut up by enormous active gullies, despite the valiant defense of unaided Chinese farmers through the

Fig. 15--Possibilities of making use of water-resources are shown in this aerial view of Bonneville Dam on the Columbia River. Cheap power from streams, from year to year, generation to generation, offers one of the most important means of making full use of Nature's resources in the interests of human welfare. (Washington National Guard)

centuries. But occasionally, in the midst of gullies, I found temple forests and grazing enclosures, to which I have already referred, where there was no erosion.

We began a series of experiments in the forested areas and on the adjoining farmed and denuded areas to run down the basic cause of reduced infiltration from bare soils and the resulting increased runoff and erosion. The decisive fact is very simple. Bared soil-surfaces tend to be sealed by muddy suspensions under the impact of rain, whereas soils protected by a layer of forest or crop-litter or grass-cover prevent the formation of muddy sealing suspensions, so that pores and interstices into the soil remain open for absorption of rain-waters to full capacity of the soil-profile. These studies answered some long-standing questions and furnished the basis for a more thorough attack upon erosion. These studies have since been expanded by many investigators to include a wide range of conditions to answer questions for different physiographic regions. Hydrological experimental areas have been patterned on the San Dimas Study, founded in 1930, to find the facts needed for conservation and control of rain-waters. A network of such comprehensive hydrological stations is urgently needed for the entire United States.

For five field-seasons (1922-1927) I made studies in the loessial highlands of North China and have recently returned from a survey of northwest China. Here soil-erosion is active on a tremendous scale that has been going on for a long time. Great labyrinthian gullies cut up the landscape into fantastic panoramas. Nowhere else on Earth have I seen soil-erosion on such a scale.

Excessive rates of erosion are shown in silt loads of streams measured recently by the

Yellow River Commission as percentage of water by weight: Yellow River at Lanchow 1942, mxm 18.75; Yellow River at Chenchow 1942, 46.14; Wei River at Sienyang 1941, 35.55; King River at Chang Chia Shan 1937, 54.70; Loh River at Chongto 1934, 63.00.

The Yellow River Commission has come to the decision that control of soil-erosion in the drainage of the Yellow River is necessary to flood-control on the delta-plain and to effectiveness of irrigation-projects. Now the Government of Free China has begun a program for the control of erosion and the conservation of soil and waters.

All of China is not equally subject to such heavy rates of erosion. More than 22 centuries ago a Chinese engineer by the name of LI BING set up one of the most successful irrigation-projects of history on the Min River, which flows clear out of the border mountains of Tibet. This project is still in excellent working condition and serves to irrigate the Chengtu Plain of 500,000 acres that supports 2,000 persons per square mile.

LI BING did not have a silt-problem to deal with but he did have bedload of boulders and gravel and annual high-waters. He correctly diagnosed this problem and prescribed simple measures and made their yearly observance a religious festival, one of which I attended on April 1-5, 1943. LI BING provided for inner and outer canals. At the time of low waters in winter the river-flow is diverted by a coffer-dam into the inner canal, while debris is dug from the outer canal; then the coffer-dam is opened and the inner canal is shut off with a second coffer-dam and is emptied and dug out to "iron dragons," set at a depth to which the channel must be excavated each year. When the work is complete, a great annual ceremony takes place at the breaking of the coffer-dam of the inner canal. Then waters are divided into the two canals to begin another irrigation-season. By dividing the two big canals into some twenty-odd lesser canals, flood-damage is avoided. So successful was LI BING in his original plan that the Chengtu Plain has not suffered from flood or famine for 2,000 years. We must honor such an engineer who was successful in controlling wild waters for the benefit of mankind and for so long a time.

It is scarcely necessary for me to cite what has been done in the United States to put the knowledge of the Earth's resources and natural forces to work here. These matters have been set forth in a galaxy of papers in this and former annual sessions of the American Geophysical Union. In the field of hydrology, information vital to establishing the sustained utility and productiveness of waters and land is being amassed in experimental installations and in practical application of such information over millions of acres of land. In the United States a beginning has been made to work out the basis for sustained and improved production of land- and water-resources in accord with principles established in the science of geophysics. While excellent progress has been made in recent years, far more needs to be done if wastage of land and water by erosion and its damaging effects are to be put under control in time to save vast areas of the best land of America.

The hazards of war, as well as those of peace, call for progressive synthesis of the several branches of geophysics.

Dynamics of flowing water present the chief hazard to a lasting adjustment of mankind to the Earth, and at the same time the greatest hope when controlled and put to highest possible uses. It is in the control and conservation of rain-waters as they fall on land and flow in streams that mankind may keep up his food-supply in abundance. Little will avail in other phases of civilization if the production of food is undermined and lessened in the face of increasing demands. When food fails, all else fails. There is no safety in a famine except in death.

As I flew over Mesopotamia with its hundreds of dry canals and ruins of former magnificence and power in the midst of present-day underpopulation and waste, I pondered the fate of mankind on this Earth. With all his boasting and pomp, man is a child of the Earth, dependent on favorable combination of natural forces and materials and their wise stewardship in the interest of survival of our civilization. The children of men may work out a lasting adjustment to the Earth only by seeking knowledge and understanding of the marvelous forces and their interrelations and by working with rather than against them in this world of wonders and the scene of the great adventure of mankind.

Soil Conservation Service,
Washington, D. C.

SIXTH AWARD OF THE WILLIAM BOWIE MEDAL

CITATION

Leo Otis Colbert

Mr. President: It is my pleasant duty to present to you a distinguished member of the American Geophysical Union who has been chosen by the Committee on the Award of the William Bowie Medal to receive the honor. The Medal is awarded for distinguished attainment and outstanding contribution to the advancement of cooperative research in geophysics.

During the last century there was great activity in the study of oceanography, but it was largely confined to biological research. As time went on it was found that such investigations could accomplish little without knowledge of the physical environment and it was also realized that the study of the oceans was important from the standpoint of geophysics, chemistry, and geology. In 1927 the interest of the National Academy of Sciences in oceanography resulted in the appointment of a Committee to investigate the existing situation.

A well-known scientist, chosen as Secretary of this Committee, was chiefly responsible for the masterly report which covered all phases of oceanographic investigations. This report led to the establishment of the Woods Hole Oceanographic Institution and to the selection of the Secretary of the Committee to be the first Director. The choice was an appropriate one, because of the career of this scientist, as an educator, as a curator in the Harvard Museum of Comparative Zoology, and as a participant in four oceanographic expeditions, in two of which he was assistant to ALEXANDER AGASSIZ.

As Director, he guided the Institution from the period of construction of the research vessel Atlantis and of buildings and laboratories through the stages of development to that of full accomplishment in oceanographic work until his retirement a few years ago.

As might have been expected, countless new problems came up which required new instruments and methods. Oceanic circulation, both horizontal and vertical, became better known through actual observations over large areas. Projects relating to marine meteorology were undertaken and the processes of sedimentation were studied. Much has been added to our geophysical knowledge of the Atlantic Ocean from the various cruises of the Atlantis and the laboratory studies of collected specimens.

Cooperation was the keynote of the program. There was close cooperation with the International Ice Patrol and with European Oceanographic Institutions. This made possible coverage of the entire North Atlantic Ocean for special problems. Support was given to projects of scientists not connected with the Institution and in two cases the results were especially fruitful. These were the development of the seismic method of exploring submarine geological structure and of means for obtaining long cores of the bottom sediments in great depths.

As a Trustee of the Woods Hole Oceanographic Institution for a number of years, I speak with some authority of these accomplishments, and I am happy to recall that Dr. WILLIAM BOWIE served as a fellow Trustee.

A recognition of some of the past work in geophysics by the former Director of the Woods Hole Oceanographic Institution is made possible this year by the award of the William Bowie Medal.

It is with sincere pleasure, Mr. President, that I present to you HENRY BRYANT BIGELOW.

REPLY AND ACCEPTANCE

Doctor BIGELOW modestly narrated some of his early associations in the work of the Union. In particular, he recalled progress in his own field of oceanography and the increasingly important applications of geophysics in that field which have so much supplemented biological research of the sea. He referred feelingly to the support given him by the late WILLIAM BOWIE. Doctor BIGELOW recounted briefly the plans, realization, and accomplishments of the Woods Hole (Massachusetts) Oceanographic Institution of which he was the first Director. His remarks recalled the splendid report and summary of oceanographic research and needs prepared by him for the National Academy of Sciences--the basis upon which the Carnegie Corporation gave generously to

make possible the attainment of a well-equipped oceanographic laboratory on the Atlantic Coast of the United States with seagoing vessels to enhance investigations of American scientists by adding large research facilities to those existing on the Pacific Coast at the Scripps Institution of Oceanography of the University of California and the Oceanographic Laboratories of the University of Washington. He stated that the American Geophysical Union and its Members had been factors in this accomplishment.

In conclusion, Doctor BIGELOW expressed appreciation of the honor conferred upon him and upon his colleagues through the award of the William Bowie Medal.

W. C. LOWDERMILK--I would like to thank all our Members and Guests, on behalf of the Union, for making the Union's quarter-century meeting so successful. The meeting now stands adjourned, but before leaving all are invited to meet Doctor and Mrs. BIGELOW and to join in a general conversazione and in light refreshments in the lobby on the main floor of the Hall of Government.

[Note: For minutes of the afternoon and evening General Assemblies and of the Sections, see pages 321-385.]

AMERICAN GEOPHYSICAL UNION

TWENTY-FIFTH ANNUAL MEETING

SECTION OF GEODESY

REPORTS AND PAPERS

Washington, D. C.
June 2, 1944

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A PLANE MAP FROM A SPHERE BY DOUBLE PROJECTION

Austin E. Jones

Figure 1 shows a method of developing a plane map from a sphere. It escapes the difficulty of some projections that theoretically extend to infinity and it undoubtedly has defects of its own. One defect is that the scale is not uniform along any radius. The development of the argument follows: Given a sphere represented by circle NEWS with radius OS = r, it is required to project: (1) From point S to a hemisphere DNC of radius 2r, with center at S; (2) the points on the hemisphere DNC, from point F to the plane surface represented by the line ANB. Then

The projection of the North Pole remains at N.

The projection of the circle of latitude 30° north falls successively at t and T.

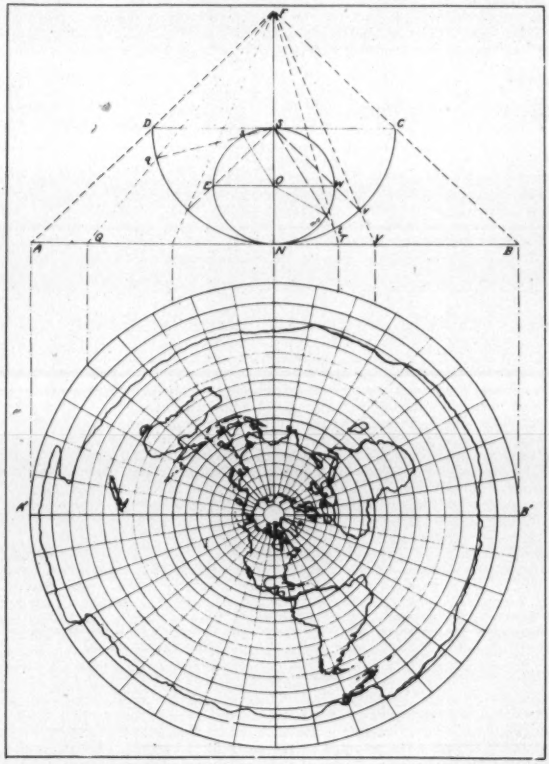


Fig. 1--A plane map from a sphere by double projection

The projection of the equator W falls at v and V.

The projection of the circle s of latitude 60° south falls at q and Q.

The projection of the South Pole S is to the equator of the hemisphere DC, and is further expanded to a circle AB representing the confines of the map. AB is further projected to the plan or map below represented by A'B', with the latitude-circles inside.

On the plane A'B', the radius, R, of any latitude-circle is represented by $R = 4r \tan (180n/4m)$. Where n is any whole number less than m and m is the number of divisions of 180° (in this case measured from the North Pole), and

The first 10° - circle	$R = 4r \tan (1 \times 180°/4 \times 18) = 4r \tan 2°5$
The second or 20°-circle	$R = 4r \tan (2 \times 180°/4 \times 18) = 4r \tan 5°$
The third or 30° - circle	$R = 4r \tan (3 \times 180°/4 \times 18) = 4r \tan 7°5$
The last point (180°)	$R = 4r \tan (18 \times 180°/4 \times 18) = 4r \tan 45°$

For the plane map developed in Figure 1, the concentric latitude-circles are drawn with the aid of the above formulas. The main land-masses are sketched in to give an idea of the distortion created in the more extended portions of the map.

Boulder City, Nevada

TRIANGULATION ALONG THE ALASKA MILITARY HIGHWAY

John Bowie, Jr.

Because of absence in the field the author did not have time to prepare an abstract or complete manuscript of this paper.

U. S. Coast and Geodetic Survey,
Washington, D. C.

RAPID METHODS FOR DETERMINING ASTRONOMICAL AZIMUTHS

C. A. Whitten

Astronomical computations for position or azimuth are not difficult for the astronomer or mathematician, even though such computations may be time-consuming. In the past few years, however, there has been a general trend toward the simplification of problems involving astronomy. This has been particularly noticeable in the development of new methods for marine and air navigation. The surveyor has benefited from some of these changes, but since the start of the war military needs have brought forth additional methods in which simplicity and reliability are the primary requirements. Simplicity implies that the method should be within the mental capacity of an average person and reliability guarantees an absence of blunders even if certain refinements have to be sacrificed.

About a year ago, a member of the armed forces requested the United States Coast and Geodetic Survey to investigate methods of obtaining astronomical azimuths with minimum effort. The method of obtaining an azimuth by measuring the altitude of a star near the prime vertical was selected as being the most practical for the needs of the services. An error of altitude or latitude has only a small effect on the azimuth of the star when the star is near the prime vertical. Accurate time is not needed in this method. Only the observed altitude and a latitude, scaled from a chart, are needed to determine the azimuth. Three publications were planned, one for the equatorial area and one each for the Northern and Southern hemispheres, allowing for a 5°-latitude overlap.

For the equatorial area, tables and graphs were prepared for 16 stars which were selected so that there would always be one star visible in the east and another in the west between altitudes 5° and 40°. The limits of latitude were selected as 15° north to 15° south. The tables and graphs had latitude and altitude as arguments. Lines of equal azimuth are shown on the graph of Figure 1.

In the publication the curved lines are printed in red. Values of azimuth can be scaled from the graphs which are accurate to three minutes of arc and they can be interpolated from the table to about the nearest minute. All computations for the tables and graphs were based on mean star-positions for 1945. Mean refraction was applied so that the observed altitude could be used directly. A star-finder was added so that the novice would have no difficulty in selecting the proper star. This publication has been used by the armed forces with satisfactory results.

In the Northern Hemisphere, Polaris is always used for precise azimuths. However, accurate time is needed for the determination of the hour-angle of Polaris. A graph showing lines of equal

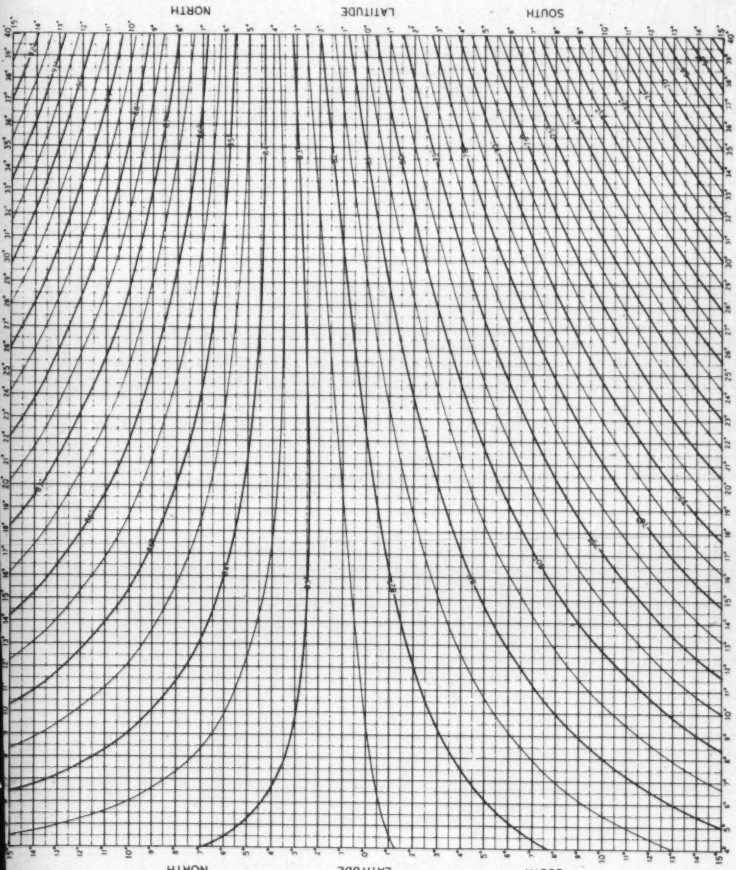


Fig. 1--Azimuth curves--Beteigeux (based on mean star position for 1945)
Star east, angle measured clockwise from north; star west, angle measured counter-clockwise from north

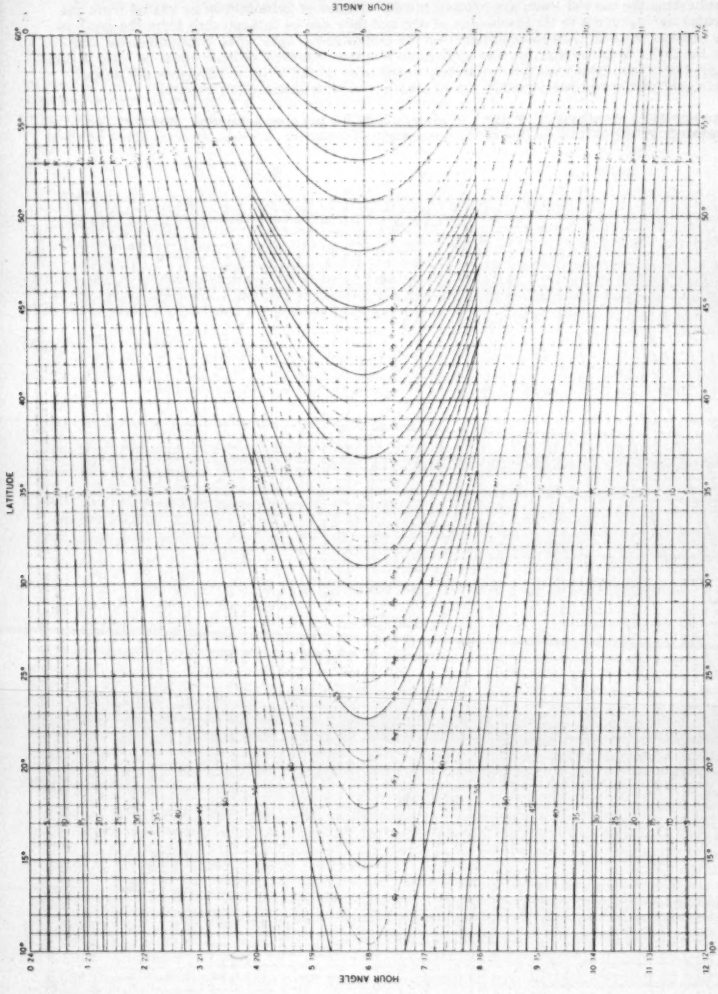
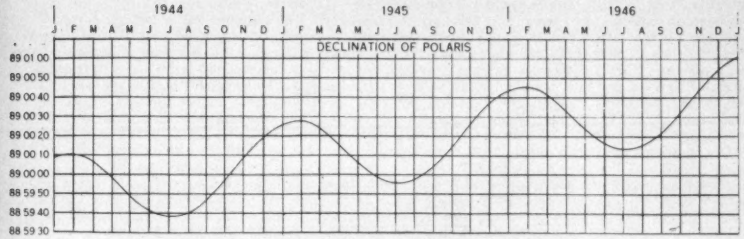


Fig. 2--Angle of Polaris in minutes of arc from north (based on declination 89° 00' 00")
Enter graph for known latitude and determined hour-angle; for hour-angle from 00 to 12
Polaris is west of north, and for hour-angle from 12 to 24 Polaris is east of north



Declination	Azimuth of Polaris						
	00′	20′	40′	60′	80′	100′	120′
° ′ ″	′	′	′	′	′	′	′
89 01 00	0.0	-0.3	-0.7	-1.0	-1.3	-1.7	-2.0
89 00 50	0.0	-0.3	-0.6	-0.8	-1.1	-1.4	-1.7
89 00 40	0.0	-0.2	-0.4	-0.7	-0.9	-1.1	-1.3
89 00 30	0.0	-0.2	-0.3	-0.5	-0.7	-0.8	-1.0
89 00 20	0.0	-0.1	-0.2	-0.3	-0.4	-0.6	-0.7
89 00 10	0.0	-0.1	-0.1	-0.2	-0.2	-0.3	-0.3
89 00 00	0.0	0.0	0.0	0.0	0.0	0.0	0.0
88 59 50	0.0	+0.1	+0.1	+0.2	+0.2	+0.3	+0.3
88 59 40	0.0	+0.1	+0.2	+0.3	+0.4	+0.6	+0.7

Fig. 3--Declination of Polaris, 1944 to 1946, and table of corrections to azimuth of Polaris for change in declination

azimuth of Polaris was prepared for use in the cases when an azimuth accurate to a fraction of a minute would be needed (see Fig. 2). Arguments are hour-angle and latitude. Computations were based on a declination of 89°00′00″. In the publication the curved lines are printed in red. Figure 3 shows a curve for the change in declination and a table of corrections for a declination other than 89°00′00″ when a further refinement is desired.

For the Northern Hemisphere, star azimuth-tables were computed for 25 stars for altitude-observation near the prime vertical. Time is not required with the use of these tables. Only the observed altitude and latitude of the observer are needed. An azimuth accurate to two or three minutes of arc can be obtained with the use of these tables. As in the equatorial publication mean star-positions for 1945 and mean refraction were used in the basic computations.

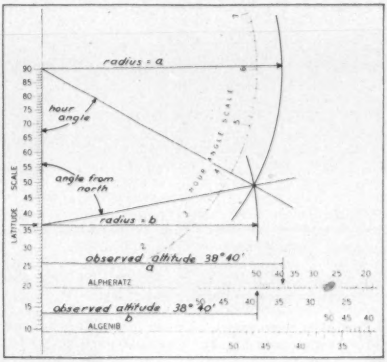


Fig. 4--Graphical solution, observer's latitude 36° 27′

In addition to the tables, a graphical method was developed and published. Using a polar stereographic projection for a base, it is possible to construct a true azimuth-angle and a true hour-angle for a given star. This is a well-known property of stereographic projections. A double scale for each of the 25 stars was calculated and drafted. These scales use the observed altitudes as the argument. Figure 4 shows a sample construction for an observation on Alpheratz. Using the radii and centers as shown, the construction may be followed in the sketch. The azimuth-angle may be measured with a protractor while the scale on the printed form will serve to measure the hour-angle. The functions for these scales were developed from mathematical principles of the stereographic projection. The accuracy obtainable from this method depends upon the care used in the construction. With reasonable care an azimuth accurate to 10′ to 15′ may be obtained.

The hour-angle of a star can be determined from the graph to an accuracy of two minutes of time. This hour-angle can be used to determine the hour-angle of Polaris. For each star a constant is given to which the hour-angle may be added or subtracted and thus obtain the hour-angle of Polaris for use with the graph of Polaris. This procedure permits the use of Polaris at any hour-angle without requiring accurate time observations.

The publication for the Northern Hemisphere has been printed and distributed. The publication for the Southern Hemisphere will be printed and distributed in the near future. Tables and scales for 20 stars for observation near the prime vertical have been prepared for the publication for the Southern Hemisphere.

The computation and compilation of the data appearing in these publications have required the efforts of many individuals. Many of the computations were made in the New York Office of the United States Lake Survey. The compilations and graphs were prepared by cartographers of the United States Coast and Geodetic Survey.

Reports have been received from units of the armed forces in various theatres of the war stating that the tables and graphs furnish an effective and rapid method for obtaining azimuths with minimum effort. They have been found to be adequate for their problems with regard to accuracy and simplicity.

It is believed that local surveyors will also find these publications valuable in making surveys they would ordinarily control with azimuths of Sun or magnetic bearings. The surveyor should always keep in mind, however, the order of accuracy obtainable from the tables and graphs, and if a precise azimuth is needed computations should be made. These computations could then be checked for blunders by comparison with the tables or graphs. After the war many men will return who will have had training in military surveys and no doubt will enter professions where their knowledge of surveying may be used. Many of the methods they will have used for military surveys can be used in making local surveys in any part of the world.

U. S. Coast and Geodetic Survey,
Washington 25, D. C.

TRANSFERENCE OF LEVELS BY WATER-SURFACE ON LAKE CHAMPLAIN BETWEEN BURLINGTON, VERMONT, AND PORT KENT, NEW YORK, JUNE AND SEPTEMBER, 1941

Arthur D. Butterfield

These experiments, conducted on Lake Champlain in June and September of 1941, on the transference of levels by water-surface readings were made as a result of a conversation with officials of the United States Coast and Geodetic Survey. It seemed a splendid opportunity to compare the results of leveling by water-surfaces with the results obtained by spirit-leveling since a level-net already existed around Lake Champlain. Moreover, the line Burlington, Vermont, to Port Kent, New York, was about midway of this net (see Fig. 1) and bench-marks were in easy access at each place, within half a mile or less of where gages would be installed.

The work of installing the gages and of making the observations was done by students in engineering at the University of Vermont working under my direction.

Description of gages--Ordinary hook-gages, as used in hydraulic-laboratory work, were installed at Burlington and at Port Kent (see Fig. 2). The hook-gage at Burlington was attached to

the vertical side of the wharf at Chiott's Boat House and adjacent to a seven-foot staff-board gage used by the Army Engineers. The hook-gage at Port Kent was attached to a pile at the steamboat-wharf landing and also there was attached to this same pile a temporary wooden staff-gage.

The water-surface readings of the hook-gages were taken in a large stilling pail in which holes were punched for the entrance of the water, thus reducing to a minimum the wave-motion.

Readings of the respective staff-gages were taken twice a day, at practically simultaneous times, during the month of June. A comparison of the four days of hook-gage readings with those of the month of staff gage readings will be given later.

Determination of the zeros of the gages--The zeros of the respective gages, hook, and staff, were determined at each separate period, June and September, by leveling from the nearest United States Coast and Geodetic Survey bench-mark, using a precise level of the United States Coast and Geodetic Survey type. (The work was done by students.)

At Burlington the elevation of the top of the seven-foot Army Engineer's staff-gage was established and at Port Kent that of the top of the backboard of the hook-gage. The zeros of the hook-gages were then established by measuring to 0.001 foot with a steel tape from these respective points to the water-surface and noting the corresponding hook-gage reading. Also the staff-gage readings were taken as a check. This method of determining the zero of the hook-gage was adopted because it was felt that it was not a wise procedure to attempt to hold a 12 foot heavy geodetic level-rod on the prick-point of a hook-gage.

The elevation of the seven-foot point of the Engineer's Staff Gage at Burlington adopted for computation was that determined from an additional series of level-observations made in 1942 by students, since the weighted mean of all observations came within 0.001 foot of the average of the level-work of 1941.

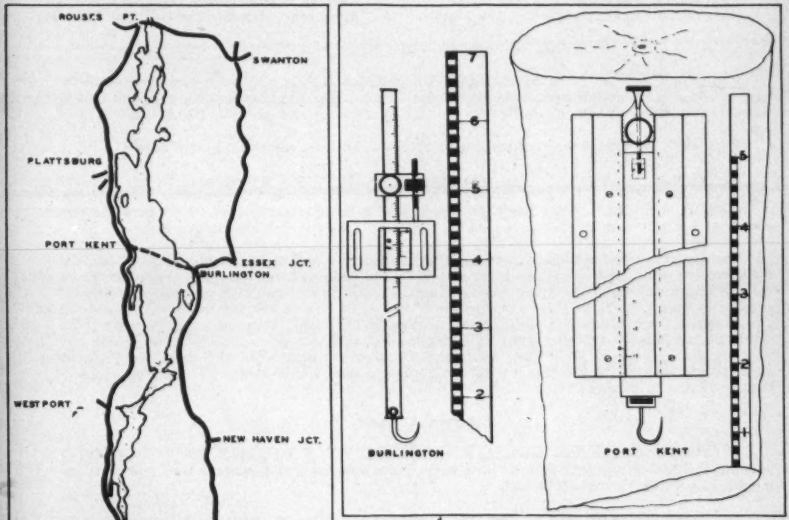


Fig. 2--Hook and staff gages

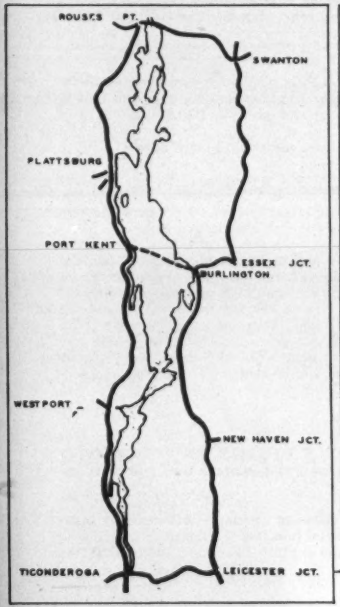


Fig. 1--Level net around Lake Champlain

At Port Kent the zeros of the respective observations in June and September were used. A redetermination of the zero of the staff-gage in September checked within 0.001 foot of that of June.

Method of taking hook-gage observations and results--Hook-gage observations were taken simultaneously at Burlington and Port Kent at each five-minute interval and extending over a period of from five to ten hours of four different days. Table 1 summarizes the observations and computations.

Table 1--Computations of results of observations from hook-gage readings

Date	No. readings	Burlington			Port Kent			Port Kent higher by
		Av. hook-gage reading	Elevation water-surface	Drop between days	Av. hook-gage reading	Elevation water-surface	Drop between days	
1941		ft	ft	ft	ft	ft	ft	ft
June 6	67	1.013	95.139		1.525	95.232		0.093
7	121	0.947	95.073	0.066	1.447	95.154	0.078	0.081
Sep.27	57	0.581	93.026		0.412	93.098		0.072
28	95	0.515	92.960	0.066	0.347	93.033	0.065	0.073
						Average		0.080

Computations of results of observations from staff-gage readings--During the 27-day period May 30 to June 25, simultaneous staff-gage readings were taken at $08^h\ 30^m$ and $19^h\ 30^m$. These readings were taken to the nearest half-tenth of a foot, except in a very few instances where they were read to hundredths of a foot. The results were:

At Burlington		At Port Kent	
Average gage-reading	2.025 feet	Average gage-reading	1.999 feet
Elevation water-surface	94.871 feet	Elevation water-surface	94.955 feet

Port Kent water-surface higher by 0.084 feet

It may be noted that when the staff-gage was installed at Port Kent an attempt was made to have the same zero as the engineer's gage at Burlington. The first observations showed that it was 0.03 foot below and the above figures give the average for the month as 0.026 foot.

Figures 3 and 4 are graphs of the fluctuations in lake-level for the different days.

Checking of results with the recording-gage of the United States Geological Survey at Burlington--The United States Geological Survey have a recording water-level gage installed about three-fourths mile north of the Army Engineer's gage used in these observations. This gage was not in operation during the observations in June but was during the observations in September.

The graph of these automatic readings (Fig. 4) has been plotted as accurately as possible on the sheets showing the fluctuations in lake-level on September 27 and 28. This graph agrees very closely with the graph at the Army Engineer's gage. The elevations of the water-surface by the recording-gage were 92.64 feet on September 27 and 92.57 feet on September 28. These elevations are based on the zero of the Army Engineer's gage as 92.50 feet, whereas our level-work from United States Coast and Geodetic Survey bench-marks make this zero at elevation of 92.846 feet. Applying a correction of +0.346 foot would give the following values for lake-level: (a) Recording-gage, 92.986 feet and 92.916 feet, and (b) from experiments, 93.026 feet and 92.960 feet, on September 27 and 28, respectively.

Summary and Conclusions

The results indicate that, assuming the spirit-level work to be correct, the water-surface leveling checked within 0.08 foot, or vice versa, assuming the water-surface levels to be correct, the spirit-leveling error is 0.08 foot.

The question may be raised, "Does the wind have any effect in causing a difference in lake-level between the east and west side of the lake?" I have been told that it does but I can find no experiments which prove it. I believe that it may, when from certain directions and of sufficient magnitude.

From these observations, it may be noted that the prevailing winds and velocities in miles per hour were: June 5, northwest and 3.4; June 6, south and 4.0; June 7, south and 9.4; September 26, northwest and 9.4; September 27, south and 6.5; September 28, south and 15.4. In other words, the wind-directions were the same at each period including the day preceding the beginning of the observations. Also the wind was light (1 to 7 mph) or gentle (8 to 12 mph), except on one day when it was moderate (13 to 18 mph). Hence, there probably would be no great difference in readings due to wind-effect.

Another question may be raised, "Is there any uniform wave-motion?" A study of the graphs

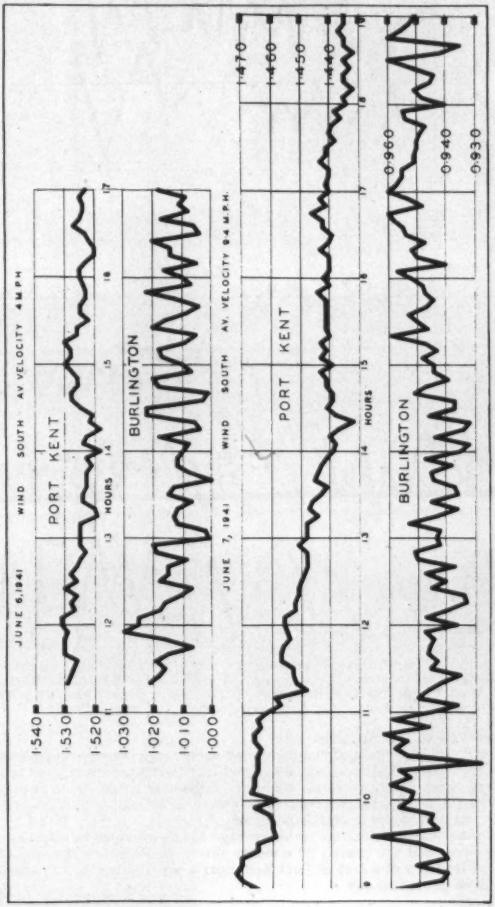


Fig. 3--Fluctuations in water-surface, Lake Champlain at Port Kent and Burlington, June 6-7, 1941 (Ranges of fluctuation, hook-gage readings: Port Kent 0.013 foot and Burlington 0.030 foot on June 6; Port Kent 0.030 foot and Burlington 0.078 foot on June 7; drop between June 6 and 7, 0.078 foot at Port Kent and 0.066 foot at Burlington)

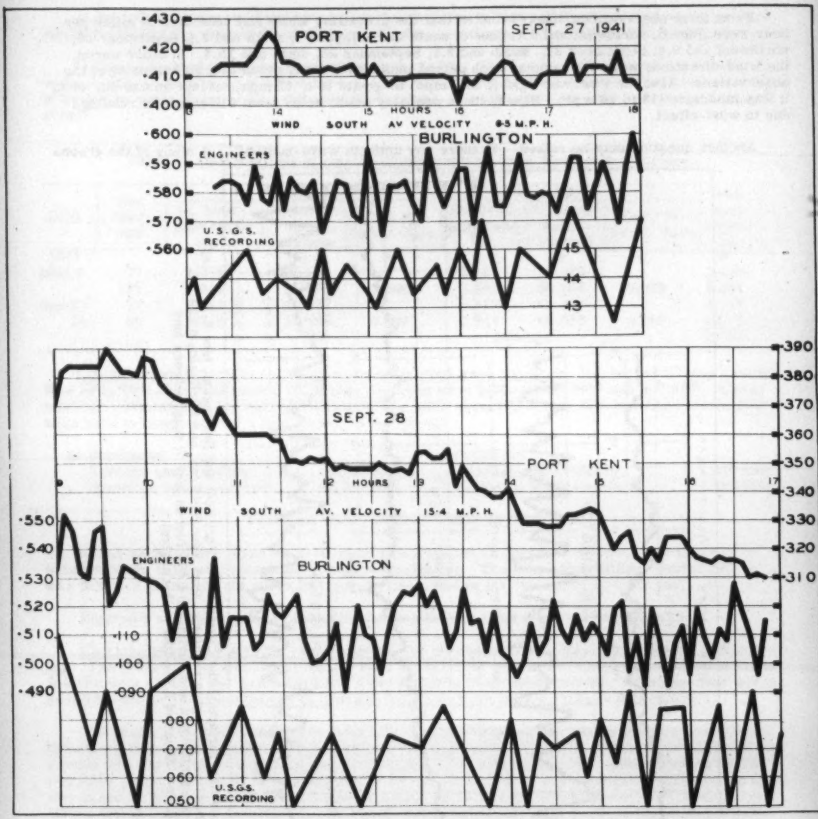


Fig. 4--Fluctuations in water-surface, Lake Champlain at Port Kent and Burlington, September 27-28, 1941 (Ranges of fluctuation, hook-gage readings: Port Kent 0.024 foot, Burlington 0.035 foot on September 27; Port Kent 0.080 foot, Burlington 0.062 foot on September 28; drop between September 27 and 28, 0.065 foot at Port Kent and 0.066 foot at Burlington)

of fluctuations in lake-level shows the following facts:

June 6: At Burlington, there are 17 maximum points, or an average of one every 20 minutes; out of the 17 there are six that are exactly 20 minutes apart. At Port Kent there are the same number or one every 20 minutes. While there seems to be no absolute relationship in the occurrence of the maxima at the two places, there seems to be a general indication that the highs at Port Kent are fairly close in time to the lows at Burlington.

June 7: At Burlington there are 31 maxima or an average of one every 20 minutes as before; out of these 31 there are seven that are exactly 20 minutes apart. At Port Kent there are 28 maxima with the same general tendency of a high at Port Kent near a low at Burlington, although perhaps less marked than on the preceding day.

September 27: At Burlington, there are 14 maxima or an average of one every 20 minutes, while at Port Kent there are 11 maxima or one every 26 minutes, with the general tendency of a high at Port Kent corresponding to a low at Burlington.

September 28: At Burlington there are 25 maxima or an average of one every 19+ minutes, while at Port Kent there are 18 maxima or one every 26 minutes as on the previous day and with a less marked relationship between the times of high at Port Kent and the lows at Burlington.

As conclusions we may note:

(a) That the changes in fluctuations of lake-level are more pronounced at Burlington than at Port Kent.

(b) That there seems to be at least some slight relationship between the highs at Port Kent and the lows at Burlington.

(c) That probably this up-and-down fluctuation is due to seiche rather than a wave-movement.

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RECENT PROGRESS IN GEODETIC SURVEYS OF THE UNITED STATES COAST AND GEODETIC SURVEY

H. W. Hemple

During the past year the Division of Geodesy, United States Coast and Geodetic Survey, has continued the program of control-surveys for use of the military organizations.

Triangulation-surveys to furnish horizontal control-stations have been accomplished in the following States: Maine, New Hampshire, New York, Massachusetts, Connecticut, Rhode Island, Michigan, Ohio, Virginia, Alabama, Florida, Texas, New Mexico, California, and Oregon. These surveys were made principally to furnish control for the mapping program of the War Department. Control was also extended in some detail along the New England Coast for use of the Coast Artillery Corps in connection with numerous installations in this region. A number of requests from the War and Navy Departments for control-surveys for special purposes have also been acted upon and accomplished. The extent of the horizontal control executed by the United States Coast and Geodetic Survey in the United States as of April 30, 1944, is shown in Figure 1.

The triangulation in the Yukon Territory and Alaska accomplished in 1943 by four parties of about 35 men each extended from White Pass north of Skagway, where a connection was made to established triangulation on the North American Datum of 1927, thence northward along the White Pass and Yukon Railroad to Whitehorse, Yukon Territory; thence following the general route of the Alaska Military Highway in a northwesterly direction to Big Delta on the Richardson Highway where a connection was made to previously established triangulation expressed on the Valdez Datum. Along this arc connections were made to stations on the 141st meridian at the International Boundary between Alaska and the Yukon Territory. The arc in western Alaska was continued from Ruby following the Yukon River westward and southward until opposite Unalakleet and thence westward to that town on Norton Sound; thence northward and westward on the Seward Peninsula to Teller on Port Clarence. This arc was also extended northward to Kotzebue Sound.

Bases were measured at White Pass, Lake Bennett, Carcross, Takhini, Canyon Creek, Burwash Landing, White River, and at Tanacross along the Military Highway and at Unalakleet and Teller in western Alaska.

Elevations for all stations were determined by means of trigonometric leveling by the triangulation-parties. For the triangulation along the route of the Alaska Military Highway where spirit-leveling was accomplished, the trigonometric leveling was controlled by frequent connections to bench-marks. In the Seward Peninsula and on Norton Sound the trigonometric leveling was controlled by references to sea-level determinations made at Unalakleet, Port Clarence, and Kotzebue.

The theodolites used were the Parkhurst type with a circle nine inches in diameter graduated to read by means of micrometers to single seconds. Directions were observed from 16 positions of the circle, and any position deviating in excess of 5″ from the mean value for that direction was reobserved.

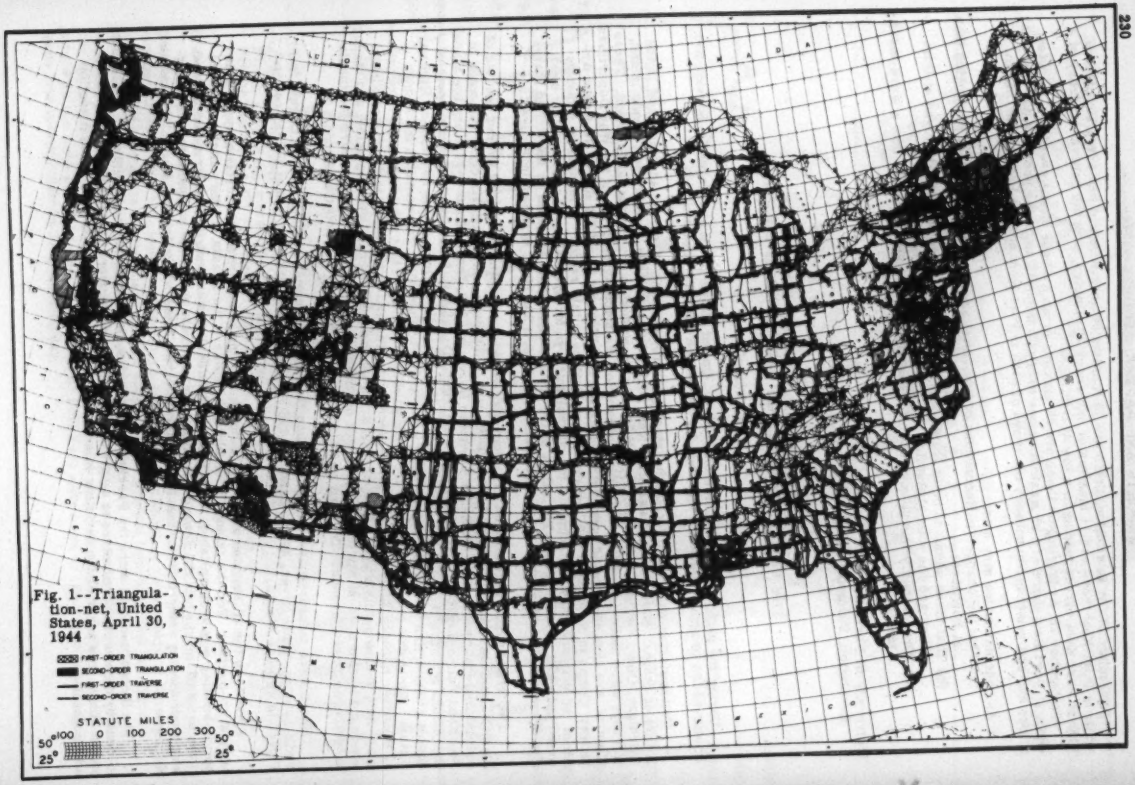


Fig. 1--Triangulation-net, United States, April 30, 1944

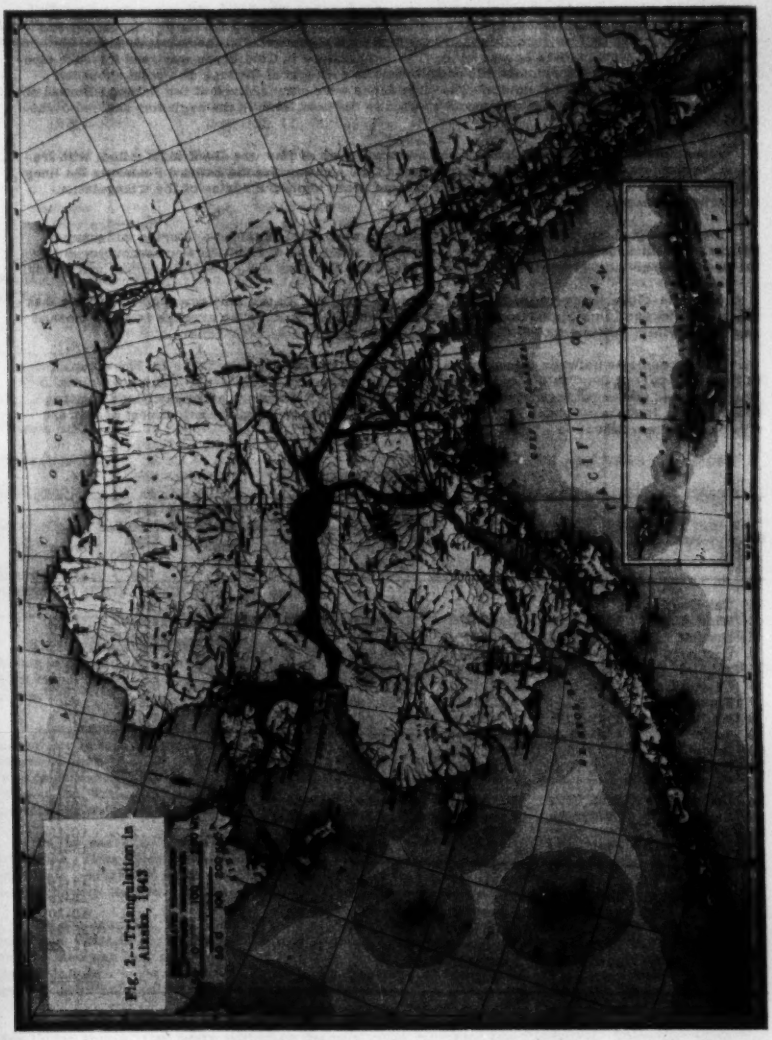


Fig. 1.--Triangulation in Alaska, 1943

The invar tapes used for base-measurement were of the ribbon type, 50 meters between terminal points. On most of the bases measured in Alaska and the Yukon Territory, the taping was done over four inch by four inch stakes and the tapes were supported at the two ends and at the middle point. A tension of 15 kg was used. The temperature in Centigrade was read for each tape-length by means of two thermometers, one attached to each end of the tape at a point about one meter outside of the terminal points. The invar tapes were standardized at the National Bureau of Standards for the same method of support as used in the field, both at the beginning and end of the field-season.

Along the Alaska Military Highway, the average length of line was about eight miles, with frequent supplemental stations established adjacent to the highway. In the Seward Peninsula the lines averaged from 15 to 20 miles in length. Prominent peaks along the routes of the triangulation-schemes were located by intersection.

Electric signal-lamps actuated by dry-batteries were used as targets. During midsummer the period of darkness in these northern latitudes is small. No difficulties were encountered in the use of signal-lamps because of this, however, since the days were usually overcast and cloudy.

Triangle-closures averaged 1."20 for the work along the Alaska Military Highway, with a maximum of 3."95 and 178 stations occupied. For the work west of Ruby the average triangle closure was 1."16, with a maximum of 3."83 and 82 stations occupied.

The agreements between measured bases in Alaska are as shown in Table 1. The comparisons in the lower part of the Table 1 are incomplete because the adjustment of the arc from Valdez to Fairbanks and thence to Anchorage has not yet been made. Field-work along the Glenn Highway from Palmer to Cooper Center will be accomplished this summer and the adjustment of this arc will be made thereafter.

Table 1--Alaska base-data

No.	Base	Length	Log	Before adjustment		After elimination of angle and side discr.		Between
				Prop. part	Sixth place log	Prop. part	Sixth place log	
		meters						
1	Tai-Skag							
2	White Pass	2770.8978	3.4426205	1/18,000	+23.98	1/30,200	+14.4163	1- 2
3	Bennett	3804.2968	3.5802744	1/41,000	-10.54	1/32,000	-13.5450	2- 3
4	Carcross	4010.8054	3.6032317	1/48,000	- 9.11	1/38,000	-11.3236	3- 4
5	Takhini	4727.3292	3.6746158	1/70,000	- 6.23	1/46,000	- 9.4467	4- 5
6	Canyon Creek	6783.7416	3.8314693	1/790,000	+ 0.55	1/2,900,000	- 0.1499	5- 6
7	Burwash	4955.1204	3.6950542	1/24,400	-17.77	1/26,000	-16.6667	6- 7
8	White River	5538.7965	3.7434154	1/28,000	-15.64	1/29,000	-14.9945	7- 8
9	Tana	7967.2544	3.9013087	1/14,250	+30.47	1/45,400	+ 9.5687	8- 9
10	Beales	7966.4503	3.9012649	1/41,000	-10.54	1/25,700	-16.9038	9-10
11	Chena	5960.7615	3.7753017	1/157,000	- 2.77	1/163,000	+ 2.6615	10-11
12	Clear	17907.8864	4.2530443	1/82,000	+ 5.31	1/59,000	+ 7.3582	11-12
13	Unalakleet	5192.9371	3.7154131	1/124,800	+ 3.48	1/25,500	+17.03	12-13
14	Teller	6972.9628	3.8434174	1/161,000	- 2.70	.....	.....	13-14
15	Miller	3063.6025	3.4862324	1/398,000	+ 1.09	.....	.....	10-15
16	Willow Creek	6715.4603	3.8270758	1/19,000	+22.80	.....	.....	15-16
17	Stuart	1798.5725	3.2549280	1/18,200	-23.90	.....	.....	16-17
18	Tsina	1294.0331	3.1119454	1/136,000	+ 3.20	.....	.....	17-18
19	Worthington	1769.0642	3.2477436	1/25,700	+16.90	.....	.....	18-19
20	Wortman	1807.3192	3.2570349	1/25,250	-17.20	.....	.....	19-20
21	Valdez	3164.4959	3.5003045	1/23,700	-18.30	.....	.....	20-21
22	Summit	2672.6005	3.4269340	1/31,000	+14.20	.....	.....	12-22
23	Broad Pass	6045.3249	3.7814197	.....	.....	.....	.....	
24	Peters	7607.4411	3.8812386	1/21,300	-20.40	.....	.....	23-24

Differences in datums in Alaska, based on field-computation of Valdez Datum and of the North American Datum of 1927 at Beales South Base at Big Delta and at Besboro on Norton Sound between the St.Michael and the North American datums of 1927 are as follows:

Station	1927-datum	Approximate Valdez Datum	Difference
Beales South Base (Big Delta)	Lat. 63°54′ 24.″483	14.″655	+ 9.″828
	Long.145 47 12. 317	43. 214	-30. 897
		(about 0.33 mile)	
	Approximate 1927-datum	St.Michael Datum	Difference
Besboro (Norton Sound)	Lat. 64°07′ 25.″946	27.″287	- 1.″341
	Long.161 18 35. 242	12. 058	+23. 184
		(about 0.2 mile)	

The differences between the Yukon Datum at the 141st Meridian marking the International Boundary between the Yukon Territory and Alaska, and the North American 1927 datum are shown in Table 2.

Table 2--Comparison Yukon Datum and North American Datum of 1927

Station	Geographic north latitude and west longitude		Azimuth		To station	Distance	
	I B C	C and G S	I B C	C and G S		I B C	C and G S
	° ′ ″	″	° ′ ″	″		meters	meters
Tanana (IBC)	62 47 53.772	55.756					
	141 14 14.127	11.511					
Starvation (IBC)	62 43 51.872	53.800	120 57 13.2	36.0	Tanana	14607.7	14608.4
	140 59 30.260	27.647					
Airs (IBC)	62 34 42.335	44.278	198 33 57.6	20.5	Starvation	17951.6	17951.8
	141 06 12.267	09.799					
Dave (IBC)	62 33 20.625	22.520	101 42 06.8	31.4	Airs	12585.9	12585.9
	140 51 49.154	46.693	161 28 35.9	60.7	Starvation	20618.5	20618.5
Boundary-monument 162 (IBC)	62 38 17.29	19.346					
	141 00 00.00	57.440					

Difficulties of operating in rough country such as in Alaska and the Yukon Territory far from bases of supplies are many. The parties must be entirely self-sufficient, and each member of the party must be able to take care of himself when on detached duty under the most primitive conditions.

Along most of the Alaska Military Highway transportation-movements were by truck. The actual sortie into the mountain stations was by pack-horses from the main highway and in many cases by back-packing. Along the stretch in the vicinity of the International Boundary the highway was impassable, and aeroplanes were resorted to. South of Carcross, Yukon Territory, the facilities of the White Pass and Yukon Railroad were used. On Lake Bennett and at Kluane Lake boats powered by outboard motors were used.

To the westward aeroplanes were used almost exclusively, except for transportation by boat along the Yukon River and in Norton Sound. In the interior the planes landed on lakes near the mountain triangulation-stations, and it was then necessary to back-pack the equipment and supplies to the survey-stations. In some cases these back-packs were in excess of 20 miles.

On one occasion, while most of the party operating in the west was en route from Unalakleet to Moses Point in Norton Sound, the ship on which they were being transported experienced engine trouble and was long overdue. Vessels plying in the Bering Sea and Norton Sound are very few; and as this is a region of heavy storms and a great deal of fog, we had a period of considerable anxiety before the ship finally made port.

Two leveling-parties, each consisting of two observing-units, operated throughout the year in the United States. One party worked on the west coast in Oregon and California. The other party

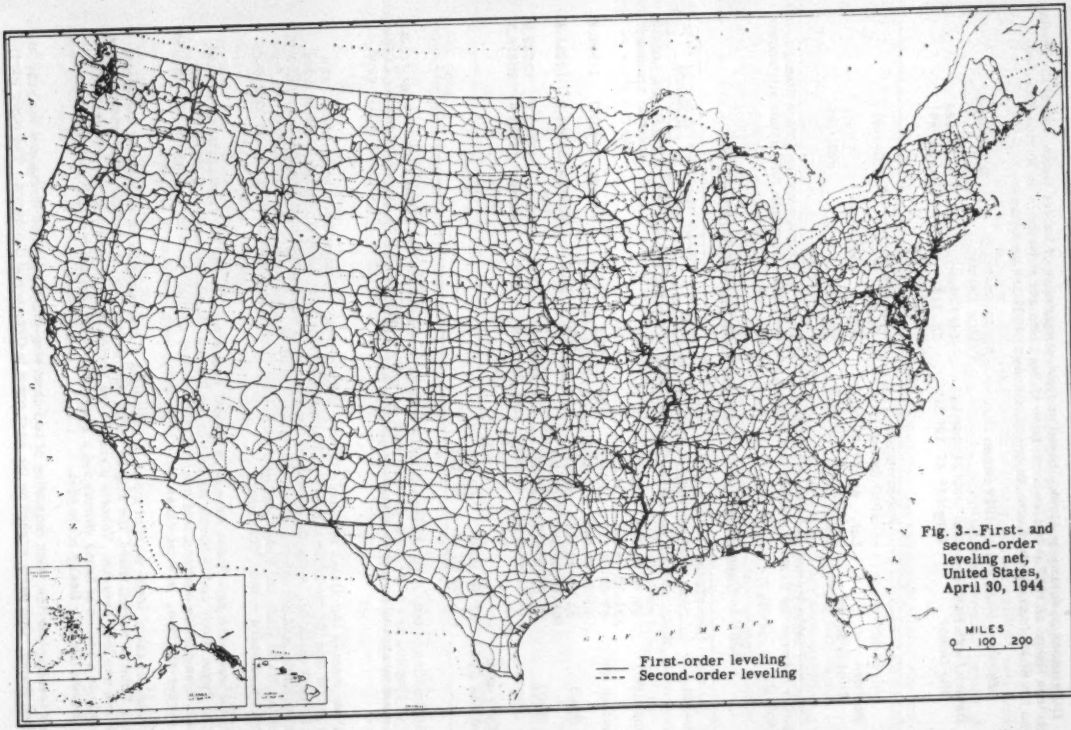


Fig. 3--First- and second-order leveling net, United States, April 30, 1944

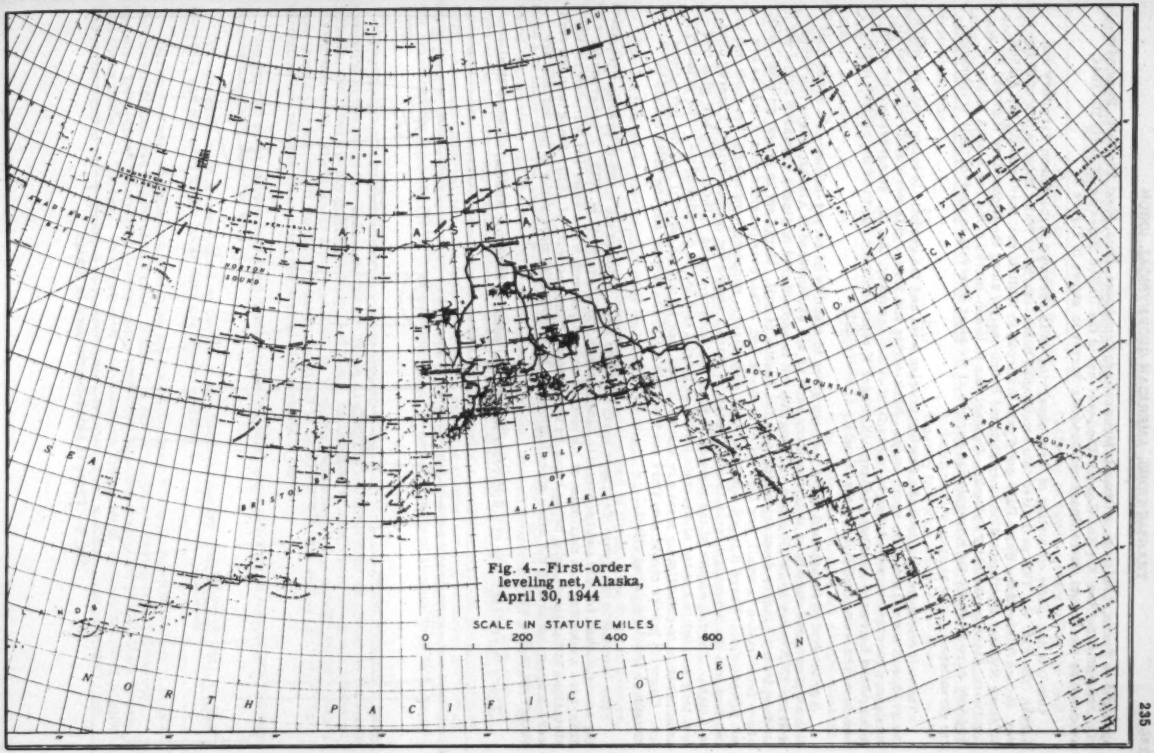


Fig. 4--First-order leveling net, Alaska, April 30, 1944

operated in Texas, Louisiana, Alabama, Mississippi, Tennessee, Ohio, West Virginia, Pennsylvania, and along the New England Coast. The level-net of the United States as of April 30, 1944, executed by the United States Coast and Geodetic Survey is shown in Figure 3.

One leveling-party consisting of three observing-units operated in the Yukon Territory and Alaska (see Fig. 4). This party tied into established bench-marks at White Pass, north of Skagway, thence followed the White Pass and Yukon Railroad to Whitehorse; thence along the Alaska Military Highway to a connection to established bench-marks along the Richardson Highway at Big Delta, Alaska, south of Fairbanks. Connections to bench-marks along the Alaska Military Highway were made by the triangulation-parties at frequent intervals to control their trigonometric elevations.

These leveling-parties used the Fischer precise level and the geodetic leveling-rods on which the graduations are painted on invar strips. Back-sights and fore-sights were made equal and all necessary precautions were taken to insure first-order accuracy, that is, an agreement between forward and backward runnings of $(4\text{ mm }\sqrt{K})$ where K represents the length of the section in km. Bench-marks were established approximately at every mile.

A great deal of thought and study has been given to stability of survey-monuments under conditions of extreme variations in temperature such as are encountered in Alaska, where the range is from 70°F below to 100°F above. Frozen subsoil is encountered in Alaska anywhere below the surface from 12 inches down depending upon the density of soil. Marks set in gravel or sandy soil, where frost-action is small, are less apt to be disturbed. Wherever possible, bench-marks are set in bed-rock. Where it is not possible to set such marks, concrete monuments, set from one to two feet into the permanent frost-line, are used. Figure 5 shows the various types of marks used in Alaska. For the section of the highway through the muskeg-region a three-inch soil pipe five feet long was set in a mass of concrete placed at least a foot in the permanent ice. The primary consideration in establishing marks in Alaska is that they should be set well into the permanent ice. Concrete marks should also flare out from the top to the bottom and the sides should be smooth to avoid frictional effect.

The leveling in the Yukon Territory north of White Pass followed the route of previous leveling accomplished in 1910 and recoverable bench-marks were leveled to in 1943. A progressive difference amounting to a maximum of 1.5 meters occurs between White Pass and Whitehorse, the elevations at the latter point being lower by that amount from the work of 1910. Since both surveys were accomplished with the same specifications, it is evident that movements of the surface are occurring in this area.

There is evidence also of a difference in the tidal plane at Skagway, Alaska, between tidal

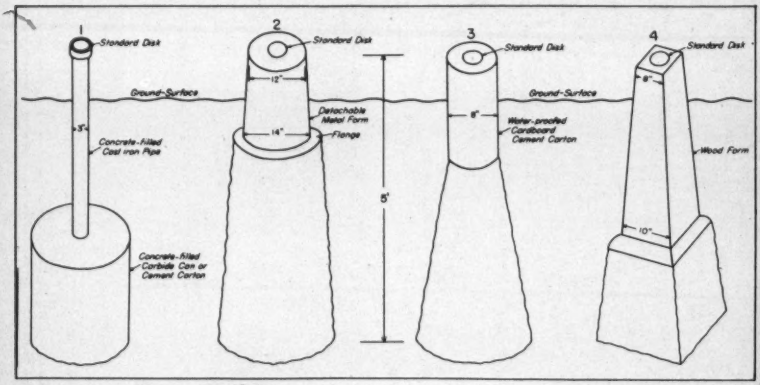


Fig. 5--Types of bench-marks used in Alaska

Table 3--Summary of geodetic work, April 1, 1943, to April 30, 1944

Work	Completed 1943 - 1944	Total to date
Triangulation, first and second order, miles	4420	94,865
Leveling, first and second order, miles	9592	326,632
First-order base-lines	20	253
Second-order base-lines	0	55
Latitude stations	10	879
Longitude stations	11	734
Azimuth stations	14	1,202
Gravity stations (pendulum)	0	1,130
Gravity stations (gravimeter)	0	37

observations made in 1908-11 and in 1943, amounting to a difference of 1.3 feet, the tidal bench-marks being that much higher in 1943 than in 1908-11 referred to the tidal plane.

If we hold the previous elevations at White Pass and at Big Delta, Alaska, the difference would be 502.8 mm too low at Big Delta and this would be distributed in 996 km. A standard tide-gage is being installed at Skagway to obtain a new determination of the tidal plane and will operate for a period of several years. Releveling will be done this year from there to White Pass. If the relationship of the tidal bench-marks to the tidal plane, as determined from the observations to be made, substantiate the change obtained in 1943 from the previous determination, then the amount to be distributed will be about 100 mm for a distance of 996 km, which will be well within first-order limitations.

In the United States, astronomical observations were made as follows: Three latitude-determinations were made in Texas and California; four longitude-determinations in Alabama, Texas, and California; and five Laplace azimuths in Ohio, Texas, and California. The two Laplace azimuths in Ohio were determined by a triangulation-party. The remainder of the astronomical determinations were made by an astronomical party.

Two astronomical parties have been working in the Yukon Territory and Alaska. Four longitudes, four latitudes, and five Laplace azimuths were determined in Canada, and three longitudes, three latitudes, and four Laplace azimuths in Alaska. Determinations of latitude, longitude, and azimuth have also been made on Attu Island with first-order specifications.

Astronomical observations in Alaska and the Yukon Territory for latitude, longitude, and azimuth are made with the Bamberg broken telescope. Scientific time-signals are broadcast by the Naval Observatory and the Naval Communications Service. Special broadcasts, in addition to the regular time-signals, were issued by the Navy for our use on this work. Longitude-observations were made to insure a probable error of not to exceed 0.02 second of time. Latitude-observations were made using the Horrebow-Talcott method and specifying a probable error of not in excess of 0".20. Azimuth-observations were made on Polaris using the method for high latitudes devised by C. H. SWICK, a description of which is given on page 32 of Part 1 of the Transactions for 1943 of the American Geophysical Union. The probable error of determination of azimuth must not exceed 0".30.

The variation of latitude-observatories at Gaithersburg, Maryland, and Ukiah, California, have continued in operation throughout the year. These are two of five observatories placed on the same latitude, the others being in Russia, Italy, and Japan, the purpose of which is to study the motion of the Earth's axis. The Russian station at Kitab in Turkestan has continued in uninterrupted operation; that at Carleforte off Sardinia in Italy, remained in operation until the spring of 1943; no information is available concerning the station at Mizusawa in Japan.

No gravity observations have been made during the year, and field-work of this nature has been discontinued until after the war.

The geodetic work accomplished by the Coast and Geodetic Survey from April 1, 1943, to April 30, 1944, and the total to the latter date are shown in Table 3.

During the year legislation authorizing the use of the State Plane Coordinate System in property descriptions was approved in Texas. There are now seven States having such legislation, namely: New Jersey; Maryland; Pennsylvania; New York; Massachusetts; North Carolina; Texas; and Glynn County in Georgia. The section of Federal-State Relations of the Department of Justice has recommended such legislation to various States throughout the country. Legislation of this

type has also been recommended by the American Bar Association and the American Society of Civil Engineers.

The use of the State Plane Coordinates in other capacities is illustrated in Maryland where the Department of State Police make extensive use of this method of location of points in their activities. The State Highway Department, public utilities companies and the railroads in Maryland are also using the system and find it of material aid.

In connection with the program of the Government to promote friendly relationships with the Latin-American Republics, a project has been initiated in cooperation with the State Department to grant fellowships to citizens of several of these countries whereby the successful recipients will spend about eight months in the United States studying geodetic methods both in the field and office. Under this program also, the Division has had a commissioned officer in South America for the past several months visiting various countries to become acquainted with geodetic operations therein and to exchange ideas with officials concerned with such surveys. It is hoped that such a program will result in the establishment of relationships which will be of mutual benefit to the United States and to the several Latin-American countries.

We have also had several officers of the Turkish Army assigned to the Washington office for intermittent periods to study our methods of processing geodetic data.

The National Bureau of Standards as in past years has continued to graduate theodolite circles and to standardize invar base tapes for our use. In connection with the testing of range-finders at the National Bureau of Standards, we have determined the distances to a number of prominent objects visible from the Bureau's testing-building in Washington.

We have continued our policy of issuing descriptions and elevations of bench-marks and descriptions, geographic and plane-coordinate positions of triangulation and traverse stations in lithoprint form.

Our computing office in New York City has functioned throughout the year and has been of considerable value in reducing the load on our Washington office. The processing of field-survey data has been accomplished in most cases immediately upon receipt of the records in the office.

We have issued several pamphlets of star-azimuth tables and graphs for rapid determination of azimuth, particularly in connection with artillery fire. These tables are described in these proceedings in the article of C. A. WHITTEN (see pp. 220-224).

The manpower shortage, and the competition for personnel with private industry where large wages are paid, has made it difficult to carry on our operations in field and office. In spite of these handicaps, however, the surveys have been accomplished expeditiously. The unit-costs have increased tremendously over that which we expect under normal conditions. No weakening of the specifications has been permitted in our requirements for accurate surveys.

U. S. Coast and Geodetic Survey,
Washington 25, D. C.

A DESIRABLE GRAPHICAL ZENITH AIR-NAVIGATION INSTRUMENT

T. A. Jaggar

The author has previously described an instrument for zenith-finding by stars [see Trans. Amer. Geophys. Union, pp. 60-61, 1938]. That instrument (see Fig. 1) uses a right-angle zenith-inspection lens system like a reflex camera hung on gimbals, having in view three pointing by adjacent stars the zenith-locus on an appropriate star-map, checking precise time. Improvements desired from an instrument-making laboratory are as follows:

(1) A beam-splitter, or semitransparent right-angle mirror replacing the reflex mirror, with the illuminated star-map (for example, Fig. 2), in the field of the horizontal beam.

(2) The star-map behind the beam-splitter adjustable by rectangular screws to secure exact superposition of the star-map stars on the actual star-images, with the fixed optical center of the apparatus, by cross-wires over the star-map frame, marking the zenith-point.

(3) A set of universal star-maps on film, originated from aplanatic star photographs, transparent star-points on a black field, suitable for the ordinary stars, and with marked astronomical coordinates of right-ascension and declination.

(4) An optical system with the widest possible angle and exact coincidence of scale between star-map and visual star-field.

(5) Object of the apparatus is to find the right-ascension and declination of the zenith-point graphically and instantaneously, by corrected radio time, in an airplane, without measuring any angles. The apparatus is to take advantage of the excellence of photographic star-projections made by the great observatories since the time of the Franklin Adams chart.

(6) Figure 1 had the objective above the mirror and brought the movable luminous cross-wires into the ocular focus, to be removed and set over a corresponding paper star-map. This ocular focus could possibly be used for a small beam-splitter acting on a small 35-mm star-map light-box close to the operator, with adjustments like a microscope movable stage. In that case the main star mirror could remain as before or might even be a large aluminized flat with wide-angle objective between it and the beam-splitter. A wide angle is very desirable so as to include navigation stars in any zenith-field and not require of the navigator unusual star-identifications of a small field.

Fig. 1--Zenith-finder model for simultaneous 3-star observations with 3-arm protractor, luminous movable cross-wires

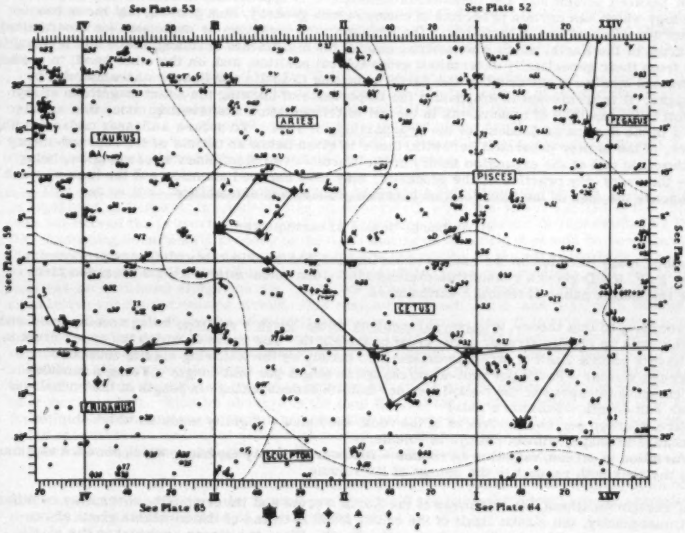


Fig. 2--Typical star-map (after London Geographical Institute)

University of Hawaii,
Honolulu, Territory of Hawaii

NEW SERVICE OF GEODETIC SURVEY

Anatol James Shneiderov

Preface--In the introduction to the Transactions of 1943 of the American Geophysical Union, the following statements are made by J.A.FLEMING: "Now, as never before, scientists in general of the Western Hemisphere need to affiliate and play their part not only in the immediate problems of application to the war effort--to which the geophysicist is contributing effectively--but in the rehabilitation of international relations and endeavors particularly necessary to investigation of earth physics;" "The Nation needs more, not less, scientific endeavor."

In the following text, these two thoughts are taken as a basis with a slight but important modification of the latter statement. In the author's opinion, not only does the American Nation need more scientific endeavor for international social and economic rehabilitation, but the world as a whole needs -- and needs badly -- a better coordination of scientific endeavor between different branches of general science, as well as between different Nations.

It is the author's firm conviction that only through an earnest cooperation of the world's scientists, (1) in trying to link and in finding the links between various branches of natural science and (2) in planning and making research in natural science fit in the frame of national and international social-economic relations -- herein lies the promise of our world's betterment and of the true progress of civilization.

The author's purpose is to contribute to the expressed idea by an attempt to find one link more between seismology and celestial mechanics -- two branches of natural science apparently remote one from the other. It is within the province of the United States Coast and Geodetic Survey to prove that the missing link between the two sciences mentioned above is geodesy.

Introduction--To specify more precisely the "when, how, and where" with respect to the missing link between seismology and celestial mechanics, it is appropriate to start with that part of seismology which has certain problems in common with geodesy, thus proving that these two sciences are adjacent one to the other. The problem is to measure the expansion (or contraction) of the crust of the Earth, which phenomenon causes the monuments of triangulation and leveling to depart from their geodetically determined geographical position, and, on the other hand, to produce stresses and strains in the crust of the Earth, resulting in faults and fissures accompanied by earthquake. It is irrelevant to emphasize the importance of knowing the exact magnitude of any variation in the position of monuments in the net of triangulation and leveling, since this article appears in the Section of Geodesy of the Transactions of 1944. To secure a clearer understanding, however, of the matter presented herewith, there is given below an outline of the rebound-theory of earthquakes and of the expansion theory of the Earth -- two disciplines whose details, being outside the every-day practice of the geodesist, may have escaped attention and the lack of which may obscure the idea of the interrelation between geodesy and seismology.

(I) Rebound-theory of earthquakes

Among many theories on the causes of earthquake, the elastic rebound-theory proposed in 1906 by H. F. REID gives a reasonable explanation -- one conforming with the observed facts -- for the immediate cause of tectonic earthquakes.

According to this theory, a universal mobility of the Earth's surface, being accompanied with stresses, sets up elastic strains in the crust of the Earth. The rocks of which the upper crust is made have a certain limit of strength determined mainly by the following elastic constants:

E = (Stress/strain) = Force per unit-area/change in length per unit-length = Young's modulus

G = (Change in thickness of the rock-layer per unit-thickness/change in length of the rock-layer per unit-length = Poisson's ratio

μ = (Stress/creep per unit-thickness of the rock-specimen = Rigidity modulus which implies change in shape, without change in volume

K = (Variation in stress/variation in volume = Incompressibility modulus, which shows a resistance of the rock with respect to the change of its volume.

At certain locations, the thickness of the Earth's crust and its composite rocks may be different. Consequently, the elastic limit of the crust, found in terms of the constants given above, varies from place to place on the surface of the Earth. When the stress approaches the elastic limit of the crust in a particular locality, the crust begins to yield -- to elongate in case of expan-

sion, or to shrink and warp in case of contraction. When stress continues to accumulate still further, the strained rock ruptures, and the rebound of the sides of the fissure (which may be seen externally if the rupture occurs on the surface, or may not be seen if the rupture occurs in subcrustial layers) produces a sudden shock propagated across the mass of the Earth and on its surface in the form of longitudinal (as sound in the air) and transverse (string-oscillation) waves known as seismic waves, which represent what is sensuously or instrumentally preceived as an earthquake.

To align the above with the original concept of the elastic-rebound theory of tectonic earthquakes, we cite the statement of H. F. REID with regard to the mass-movements of the Earth's crust at the time prior and coincident to tectonic earthquakes:

"(1) The fracture of the rock, which causes a tectonic earthquake, is the result of elastic strains greater than the strength of the rock can withstand, produced by the relative displacement of neighboring portions of the Earth's crust.

"(2) The relative displacements are not produced suddenly at the time of the fracture, but attain their maximum amounts gradually during a more or less long period of time.

"(3) The only mass-movements that occur at the time of the earthquake are the sudden elastic rebounds of the sides of the fracture toward positions of no elastic strain; and these movements, gradually diminishing, extend to distances of only a few miles from the fracture.

"(4) The earthquake-vibrations originate at the surface of the fracture; the surface from which they start has at first a very small area, which may quickly become very large, but at a rate not greater than the velocity of compressional elastic waves in the rock.

"(5) The energy liberated at the time of an earthquake was, immediately before the rupture, in the form of energy of elastic strain of the rock.

"These statements may be called the elastic rebound-theory of tectonic earthquakes; they do not broach the original cause of earthquakes, which lies in the source of the slow movements accumulating the elastic energy, but merely give the modus operandi of the accumulation and liberation of this energy."

Giving due credit to this sound statement by Dr. REID, the author wishes to add that the slow movements of mass continue all the time -- that is, even at the time of earthquakes. Therefore, it should not be thought that an earthquake causes the expansion and contraction of the crust of the Earth to cease in development, as may be understood from paragraph (3) of the above statement.

With respect to paragraph (5) of Dr. REID's statement, we maintain that the energy liberated at the time of an earthquake should be always smaller than the energy of elastic strain accumulated up to the time immediately before the rupture, and still smaller than the energy required to bring the location where the earthquake occurs to the condition of the crust-rupture. This is because of the elastic hysteresis which requires an amount of irreversible work, and, consequently a dissipation of energy, not participating in producing the earthquake.

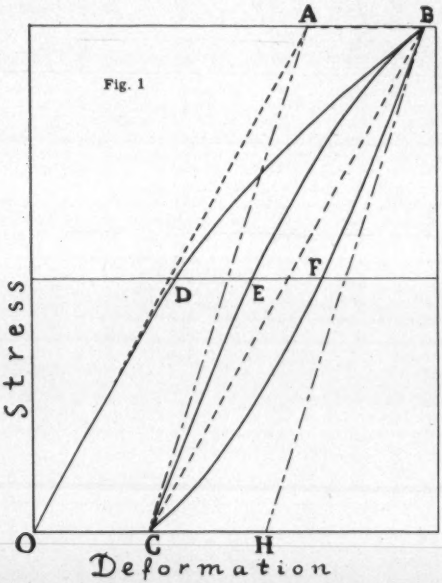
This can be seen readily from the elastic hysteresis loop given in Figure 1. This Figure may be explained as follows: In an ideal case (monocrystal), when the stress applied to the specimen does not exceed the proportionality-limit, the expansion versus stress is represented by the line OA. Assuming an adiabatic process in the deformation of the rock, it should be accompanied with the drop in temperature, because of an increase in the volume of the expanded rock. Then the expanded part is gradually heated again to the temperature of the surroundings, and, due to this heat, acquires an additional elongation AB. When the stress is decreased the line BC represents the contraction versus decreasing stress. The contraction is adiabatic, and results in raising the temperature of the rock above the ambient temperature. In some time following the contraction the rock cools and acquires its original dimension by an additional contraction for the length OC, thus completing the cycle. In the real case of the Earth's crust, the deformation takes place repeatedly and alternately in opposite directions. Consequently, as we do not know when this process of alternate deformation has started, we never observe either OA or OB (for the strains beyond the limit of proportionality). What we observe is the loop BECFB for an elastic rock, or the loop ABHCA for a perfectly plastic rock. Both types of hysteresis represent a process of entropy, and their areas represent the amount of dissipated energy, accumulated during the straining of the crust, but not participating in the propagation of the seismic disturbance.

According to our computation, the amount of energy dissipated in elastic hysteresis of basalt rock may range, approximately, from 8 per cent to 40 per cent of the total energy expended in the production of a strain capable of rupturing the rock.

Inasmuch as the rebound-theory of earthquakes "does not broach" the original cause of earthquakes, while the expansion-theory of the Earth deals with the original and immediate causes in which lie the source of the slow movements of the crust with a subsequent accumulation of the elastic energy necessary for the rebound theory to be fully grounded, an outline of the theory of the Earth's expansion is next given.

(II) Earth-expansion theory

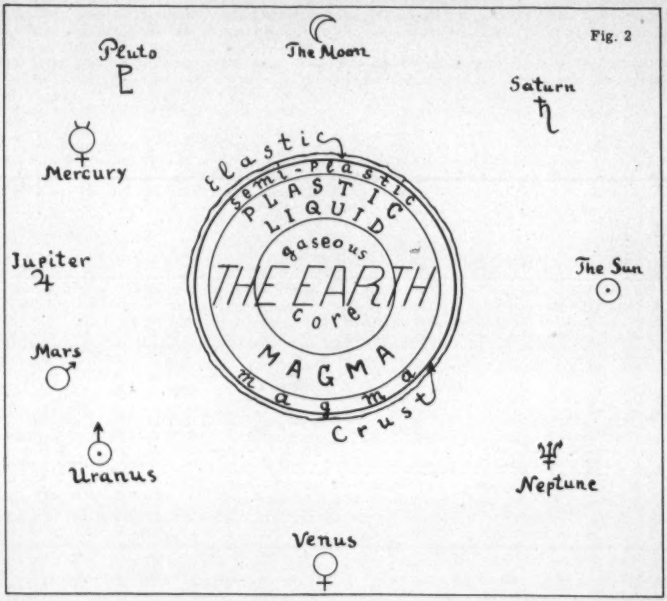
According to the exponential theory of gravitation presented last year [see 1 of "References" at end of paper], the Earth contains a gaseous core formed of atomic-electronic gas of great density and elasticity, comparable with those of heavy metals and steel, respectively. Thus, the Earth's

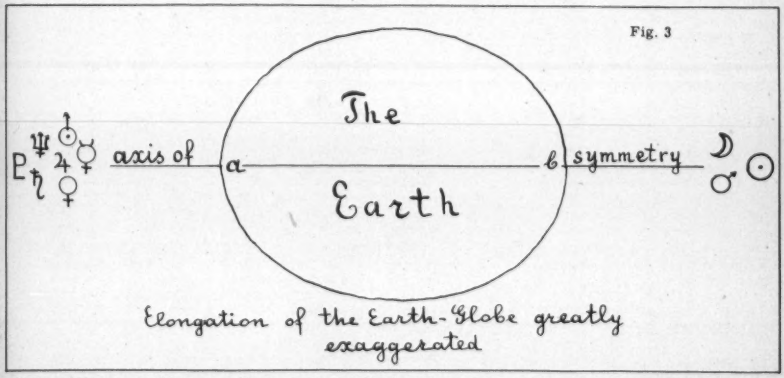


crust is under a constant pressure from inside, similar to the pressure on an inflated balloon. The equilibrium is held by elastic forces present in the solid crust and sub-crustal layers and by an external pressure exerted upon the Earth by the LeSagian field. Again, the picture of the equilibrium is similar to that of an ordinary balloon inflated with gas - equilibrium is held by the elastic strain in the balloon's wall and by external atmospheric pressure. Hence, the expansion-theory of the Earth explains the origin of strains and stresses in the Earth's crust and, consequently, it gives a firm foundation for the rebound-theory of earthquakes.

Unlike a rubber balloon, however, the Earth's solid crust is not as elastic as rubber is, but is rather as elastic as glass. The Earth's surface may be compared with a spherical film of glass, irregular in thickness and elastic modulus, laid over a semi-plastic sub-crustal magma, supported on the plastic layer of inner magma which is pressed outward by the pressure of the gaseous core of the Earth.

Slight changes in the external field, such as those caused by variations in configuration of planets, the Moon and the Sun (syzygies, tidal forces, orbital perturbations, etc.), and by cosmic varia-





tions [2], cause variations in the form of the Earth and result in breaking the equilibrium and in rupturing the crust and/or sub-crustal layers with consequences of earthquakes described by the rebound-theory.

The process may be visualized by Figure 2. The gravitational action of celestial bodies around the Earth tends to expand the Earth evenly in all directions close to the equatorial plane of the Sun (so far as planetary orbits group near the equatorial plane of the Sun). As a result of such action the Earth changes its form from a perfect sphere (we assume spherical shape of the Earth as a first approximation) into an oblate ellipsoid of revolution, with its axis normal to the resultant plane of the expansion. So far as the expansion is even in all directions, the rupture of the crust may not occur, or it may occur with great violence due to the longer, and therefore greater, accumulation of stress.

In Figure 3 another possible configuration of the Sun, the Moon, and the planets around the Earth is given. In this case, gravitational forces exerted by the grouped celestial bodies tend to make the Earth expand in two opposite directions mainly, changing its shape into a prolate ellipsoid of revolution, with its axis along the line of maximum expansion lying in or close to the equatorial plane of the Sun.

Sharp (comparatively) bendings of the Earth's crust at the points a and b of the prolate ellipsoidal Earth (see Fig. 3) represent favorable places for accumulation of stresses in the crust at these particular localities. The Earth's crust expands at points a and b at a much greater rate than at other places on the Earth, the rate of the variational expansion rising from a few cm per 100 km per year to several cm per 100 km per day, with resulting ruptures and faults in the crust and subcrustal layers at the bulges a and b, when elastic limit of the crust is overrun by the arisen strains. Hence, an earthquake

(III) Geodetic variations prior to an earthquake

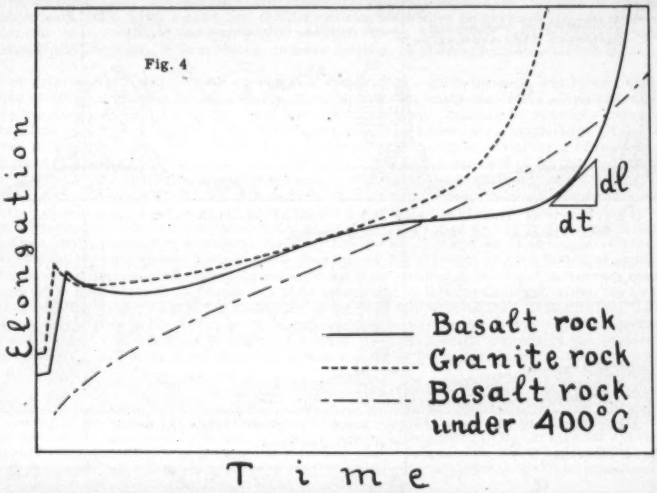
In spite of the brittleness of rock-specimens, the Earth's crust, composed of such rock, possesses a great amount of elasticity and plasticity. Here again glass may be referred to as a relevant material analogically, representing elastic and plastic properties of the crust. A long strip of a thin film of glass may be rolled and folded. A well-known fact is that a straight glass rod (about one-fourth inch in diameter) should not be inclined against some wall, or other support, because in a few days it becomes bent, and even crooked, under its own weight. Ordinarily, however, glass rods are "springy" like steel, when bent quickly but slightly. A little excess of quick bending breaks the glass, displaying its fragile property. Exactly the same behavior may be assumed with respect to the Earth's crust when subjected to a stress.

When the stress is strong, but develops gradually, the crust expands or warps and folds without rupture, in the same manner as a film of glass folds or a glass rod bends. When the stress develops rapidly, however, the rate of expansion or contraction becomes large also. For a particular rock, and consequently for a certain part of the Earth's crust, there is a certain critical rate of variation in its length when strains formed in the crust by the stress applied are greater than the crust can stand without breaking; and then the crust breaks and an earthquake is produced.

When at a given locality the crust changes from a relaxed condition (zero-strain) to the breakdown condition at a critical strain, the increase of the tension in the Earth's crust develops gradually; the relative movements of the crust at the given locality, with respect to a reference-point or points at some other locality are also more or less smooth.

A characteristic curve of the rate of expansion for different rocks subject to a certain constant stress may be constructed on the basis of the expansion of the crust against time. Taking abscissa for the time-axis and ordinate for increase in the length of a determined distance in the locality under observation, the family of curves shown in Figure 4 may be expected. The curves of Figure 4 were obtained by a group of scientists of the Society for Study of Manchuria in 1924-25, and are reproduced here from memory; and they are, therefore, more of a qualitative character than quantitative. Parallel investigations should have been made, however, in the past 20 years by several institutions here in America and abroad. Consequently, the data necessary for plotting the curves with their exact positions in the elongation-time coordinate system should be available. All the curves of this family are obtained with the force (stress) held constant, or approximately constant, when applied to the specimen. Therefore, another set of experiments covering a variable stress imposed upon different specimens of rocks may be necessary.

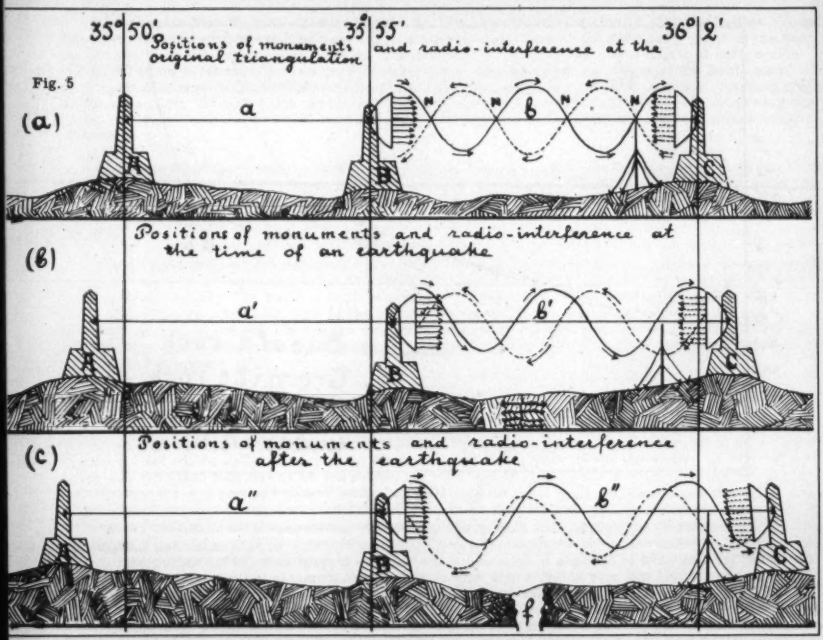
When the process of yielding of rocks subjected to extension or compression is sufficiently studied, the numerical data accumulated will give the values for the strains in the rocks -- and hence in the Earth's crust, so far as the crust is composed of the tested specimens of rocks -- beyond which, or at the vicinity of which, the rock ruptures and an earthquake results.



It is a fact known to geodesy, that after great quakes, the monuments in the disturbed region are found to be disarranged and displaced with respect to one another. In such cases new triangulation and leveling have to be made to correct for the changes brought about by the earthquake. Such retriangulations will give reliable data with respect to two moments in time - one when the last triangulation was made prior to the earthquake and the other, a triangulation following the earthquake. Thus, the picture obtained from such a set of data is static in its character. There may be several or many changes in exact geographic positions of the monuments in between these two moments of time, due to the continuous movements of the Earth's crust.

In the meanwhile, the data taken from the distorted triangulation and leveling may be used for second- or third-order geodetic measurements, introducing an error which may be considerably above the instrumental error of observation. It should be realized that a change in distance between two movements may be much greater some time before an earthquake than the change found after the earthquake. Figure 5 illustrates this possibility and may be described as follows:

On a certain date three monuments A, B, and C of the triangulation-net were erected and their geographical latitudes determined as 35°50′ north, 35°55′ north, and 36°02′ north, respectively. An ultra-short wave radio-transmitter installed at B sends a beam of energy (solid arrows from the transmitter) directed toward the parabolic (or other appropriate form) mirror installed at C. The beam of energy from the transmitter sets up electro-magnetic oscillations in the space between the transmitter on B, and the reflector on C. This oscillation is shown in Figure 5 as sinusoidal waves by the solid line. It may be called a running electromagnetic wave, the zero-point energy of which propagates along the line ab with the velocity of light. Upon reaching the reflector at C, the beam of energy is reflected backward (dotted arrows) and set up in the same space another sinusoidal wave of electromagnetic oscillations (dotted sinusoidal waves), running in the opposite direction with respect to the wave sent out by the transmitter at B. The frequency (or wavelength) of the incident and the reflected oscillations are the same, as well as the velocities of their propagation along the line ab. By tuning the reflector for a standing wave, that is moving the reflector along the line ab, the zero-points of energy of the incident running waves arrive at certain distances from the transmitter exactly at the same time when the zero-points of energy of the reflected running wave arrive at the very same spots. These points are called nodes (indicated by N) and the two electromagnetic waves superposed in the described manner are called a standing electromagnetic wave. An antenna installed close to the reflector at C, in such a way as to be exactly



at the node N of the standing wave, will receive no signal; this is natural, because the energies of both running electro-magnetic waves are of zero-value at that particular point in the air. Any increase, or decrease in the distance between the monuments B and C, comparable with the length of the wave operated in the radio-transmitter, will destroy the standing-wave arrangement. Consequently, a signal will be received by the antenna and the voltage - amplified by a suitable electronic device - will register its RMS value by means of an alternating-current voltmeter, or an oscillograph. Such a condition is given diagramatically in Figure 5 (b) when the Earth's crust, "pale" from the terrific strain of an expansion, ruptures (vibrating arrows in the crust in the Fig.) sending out seismic waves of destruction. The position of the antenna in this case shows clearly that it is out of the zero-point of electromagnetic waves. As a matter of fact, there is now no such a point of zero-energy in all the line between the monuments B and C - the standing wave has been destroyed. The magnitude of the voltage coming from the air through the antenna and registered by the oscillograph will show the magnitude of the displacement of the monuments along the line a'b'. Figure 5 (c) shows a condition after the earthquake, when a fault between B and C occurred, and a fracture f formed in the crust. Figure 5 indicates that it is quite possible to expect $a' > a'' > a$ and $b'' > b' > b$, that is, a distance between the monuments A and B should be larger just before the earthquake, while the distance between B and C should be larger after the earthquake.

From the foregoing discussion, it seems desirable to have not a statical picture of changes caused by an earthquake in the triangulation-net but a dynamical picture representing continuous changes in the net, due to the movements in the Earth's crust before and after the earthquake. This dynamical picture would be equivalent to a continuous triangulation and leveling of the region included in the Figure. It would give, therefore, exact geographical coordinates of the monuments at any given moment of time, beginning from the first triangulation through the time when such continuous triangulation was carried out.

On the other hand, this scheme of continuous triangulation should give excellent data for study of movements of the Earth's crust and of their relation with other geophysical and astronomical phenomena, such as atmospheric pressure, variations in the geoelectric and geomagnetic fields, in latitude and longitude, in tidal forces, in solar activity, in planetary configurations, etc.

By determining the rate of the expansion of the crust at a given moment, that is rate of increase of distance between the monuments, it can be found to which part of the elongation-time curve the given moment of time and the elongation correspond. This can be done by a comparison of the slope of the experimental curve with the $(\partial l/\partial t)$ of the continuous triangulation. If the observed rate of expansion lies on the part b-a of the curve (see Fig. 4) the process of expansion just began; a correspondence of the observed value to that on the part a-b of the theoretical curve will indicate a slow process of strain-development, without an immediate danger of earthquake. When it is found that the observed $(\partial l/\partial t)$ corresponds to the values lying on the part b-c of the curve, it should be considered a fair indication for the probability of an earthquake in the location under observation. The location taken under an earthquake warning should be given a thorough and expedient study, in order to determine the other factors which might serve as trigger-forces in rupturing the strained crust. In case of the presence or the approach of such forces of appropriate direction and sufficient magnitude to make up to the final yielding of the crust, a warning should be issued to the population of the possibility of an earthquake in this particular location, the line (or site) of greatest danger, and of the magnitude of the expected disturbance. Remembering that the greatest part of loss in life and property resulting from an earthquake is due to its unexpectedness, one may assume that thousands of lives and millions of dollars worth of property can be saved by such scientific prediction, based on actual measurements of the expansion of the Earth's crust.

(IV) Radio interferometer

Thus far, the possibility of earthquake-prediction through the service of a geodetic survey has been outlined in the preceding chapters, and it has been found desirable to arrange for continuous triangulation and leveling - at least at the locations where seismic activity is expressly manifested. The instruments with which the necessary observations could be performed will be discussed below and the locations of the experimental stations suggested.

For a continuous triangulation the author suggests a continuous measurement of the distances between the monuments of the triangulation-net, or a part thereof. In Figure 6 three monuments are indicated by points A, B, and C. As far as the three sides of the triangle ABC could be accurately determined, all elements of the triangle would be known, and therefore any departure of the monuments from their predetermined geographical coordinates would be readily recorded. There is but one exception to this statement, namely, when the three monuments A, B, and C depart from

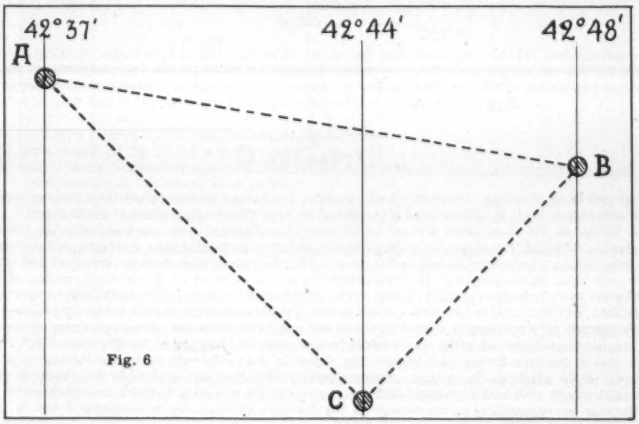


Fig. 6

their geographical coordinates in the same direction and with the same speed. Such a situation might arise, for instance, in a large landslip. But even in this case the true departure of A, B, and C from their geographical coordinates could be determined if the continuous triangulation were made over a greater area, which would include the area covered by the monuments A, B, and C. In all other cases a simultaneous movement of ABC in the same direction and at the same speed may be considered as highly improbable.

To measure continually the distances AB, BC, and CA and to record their values at any given moment automatically, the author proposes an electrical device which can be appropriately named a radio interferometer.

An ultra short-wave radio transmitter (wave length of the order of a few cm) installed at, say, monument A, directs its beam of electro-magnetic oscillations to the monuments B and C where two parabolic or elliptical mirrors are fixed to the monuments. The beams being reflected by the mirrors direct the reflected beams of electromagnetic oscillations back to the transmitter. In virtue of the wave-form of the oscillations, an interference between the direct and the reflected beams should be observed. This physical phenomenon with the apparatus suitably arranged will manifest itself in the form of standing electromagnetic waves in the line between the transmitter and the reflector (see Fig. 7).

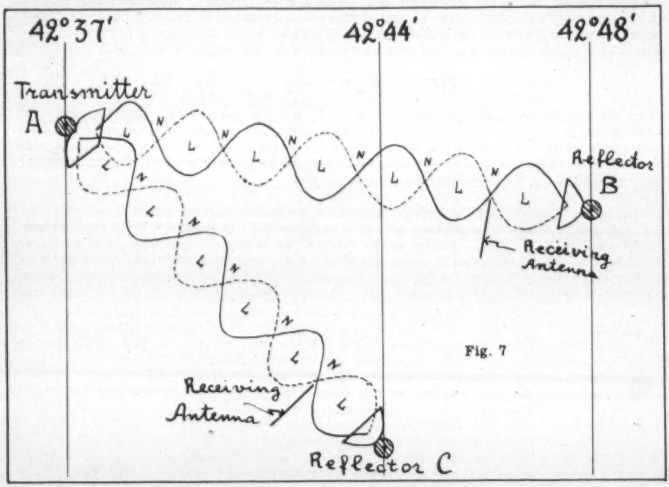


Fig. 7

By the property of standing electromagnetic waves, the voltage measured at the points of constructive interference, that is, at the loops designated by L in Figure 7, will be at about double value of the voltage at the same point without energy of the reflected wave. At the nodes the interference is destructive and therefore the voltage measured in the interfering electromagnetic beams is of zero-value at the points designated in Figure 7 by N. Consequently, a radio receiver sharply tuned to the particular wave-length of the transmitter at A will receive no signal at the nodes of the interfering beams while a double strength signal will be received at the loops. For a definite frequency of the transmitter, any variation in the beam-length between the transmitter and the reflector will be evident as a fluctuation of the strength of the signal in the receiver, because of the deviation of the interfering beams from their standing-wave arrangement. In the changes of the distance AB for a length above that of the interfering radio-wave, the signal in the receivers will pass through one or several cycles, which variation in voltage - appropriately amplified and applied to the plates of an electrical oscillograph - will be represented by a graph roughly of a sinusoidal form, each wave in the oscillogram corresponding to the change in the distance between the monuments A and B equal to the wave-length of the radio wave employed.

When a change in the distance AB is smaller than the wave-length, the variations can be determined from the graph by measuring the ordinate of the voltage-line on the oscillogram, and the variation X is given by the sinusoidal-wave formula

$$X = \lambda\,(y - A \sin 2\pi ft)/A \sin 2\pi$$

where λ is the wave-length used, A is the amplitude of the wave, y = the distance between the zero and actual voltage-line in the oscillogram, f the frequency of the vibrator, and t is the time from the moment when the signal was zero to the moment of the measured ordinate y is determined from the time-axis on the graph.

By this method, taking into account the degree of accuracy of present-day electronic devices, the author considers it possible to measure X to 0.012λ. For a distance of ten miles between the monuments, any variation of this distance for more than 0.1 mm, or 0.04 inch, or for more than $(0.1/16.1 \times 10^8) = (1/1.6 \times 18^8)$ part of the measured distance between the monuments, should be determinable. The position of the voltage-line on the oscillogram above or below the zero-line will indicate whether a contraction or an expansion of the crust takes place.

The ratio of y to t in the graph, being proportional to the rock-yield curve given in Figure 4, will represent the rate of the expansion or contraction and will permit calculation of the position of the moment on the yield-curve with consequent data for the calculation of the probability of an earthquake in the region under observation.

An installation of two transmitters, three receivers, and three reflectors in a system of three monuments (such as given in Figures 6 and 7), and of equipment to automatically record variations would represent a system of continuous triangulation. The system described should be capable of detecting and determining: (1) The expansion or contraction of the crust of the Earth; (2) the rate of expansion, and therefore, critical moments before the rupture of the crust, that is, predicting a probability of an earthquake at a given locality; (3) form, intensity, and direction of a seismic wave passing through the system; (4) strain-conditions in the Earth's crust prior to, during, and after an earthquake; (5) any variation in relative position of the monuments, thus contributing to greater accuracy of the geodetic survey; (6) differentiation of the horizontal and vertical displacements by means of polarized electromagnetic waves, thus contributing to greater accuracy in checking the leveling operations.

As to the locality of the experimental radio interferometer station, the author thinks the triangulation base-lines and the Laplace azimuths in California and other seismically active regions would be most effective places for testing and utilizing the new method.

Conclusion

Our conclusion is addressed to the United States Coast and Geodetic Survey, the Carnegie Institution of Washington, the societies of seismology, geodesy, and tectonophysics, and all other scientific organizations which in their work or research are concerned with a better and more expedient performance and study in their respective branches of natural science.

The thesis given in this paper may be stated as follows:

(1) Movements of the Earth's crust exist.
(2) Disturbance of the triangulation and leveling nets caused by the movements of the movements of the crust also exists.
(3) Elastic properties and constants of the Earth's rocks are known; therefore the curve of strain in the crust under given stress can be determined and the breaking point in the crust and the time of breaking calculated.
(4) The phenomenon of standing electromagnetic waves has long been known, and its application to the measuring of variations in distance between the triangulation-monuments is obvious.
(5) Construction and installation of radio interferometer stations present no more technical difficulties than could be overcome.
(6) Reduction of the observed values to the true values of variation, that is, elimination of interfering phenomena (heat expansion, vibrations caused by wind, strains in the structure of the monuments, etc.) can be made satisfactorily.
(7) Coverage of the United States with radio interferometer stations would serve as a truly scientific method of close-probability prediction of earthquakes.

(8) The same coverage would enable the United States Coast and Geodetic Survey to obtain accurate (undistorted) maps of this country.
(9) Invaluable service would be rendered to the study of origination and propagation of seismic waves and morphological and tectonological changes in the face of the Earth, and to geophysical research in general.
(10) Knowledge of the variation in the stresses applied to the Earth's crust at any given moment would help in finding relations between geophysical and astronomical phenomena described by celestial mechanics, thus establishing a new link between the sciences of seismology and celestial mechanics through the new service of geodesy.

Consideration of the cost of the proposed new service of geodesy may be estimated as follows:

Construction and installation of 12 experimental stations . . .	$ 66,840
Installation of 6,400 permanent radio interferometer stations .	13,760,000
Yearly maintenance:	
Personnel at 12 stations, total of 38 men	110,600
Supervision, repairs, computations, and administration for total of 1622 men, amortization, etc.	7,077,000
Expansion and improvement of the net	269,000

It is believed that an initial investment of $177,440 in a program, potentially of such great service to the Nation and to the whole human race, for so important a geophysical field, would demonstrate the feasibility of predicting seismic disturbances and hence the saving of lives and property in every major earthquake. An oncoming disaster scientifically pre-determined by the net of radio interferometers, would repay many times the costs of maintenance for many years.

Finally, the author ventures his opinion that an artificial release of the strains accumulated at a certain locality of the Earth's crust is within the possibilities of contemporary engineering. Consequently, not only would prediction of earthquakes , being within the range of engineering possibilities, benefit the people and the economics of the country, which may adopt the proposed method of tectonophysical and geodetic control of the movements in the crust, but would directly prevent or damp seismic disturbance and so contribute to the prosperity of the nation.

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THE ZENITH-CAMERA FOR GEOGRAPHIC LOCATION

Julius L. Speert

Engineers and astronomers are already familiar with the use of the transit and theodolite for field-determination of latitude and longitude. In recent years the prismatic astrolabe or equiangulator has come into extensive use by the Army Air Forces for the determination of geographic positions [see Trans. Amer. Geophys. Union, Part II, pp. 199-207, 1942]. The latest instrument developed for this purpose is a camera which photographs a portion of the sky immediately surrounding the zenith. The finished photographic plate shows the stars in the vicinity of the zenith and a fiducial mark which represents the zenith itself. The camera takes a 4- by 5-inch glass plate and exposes a square field approximately 9°.5 on a side. From measurements on the plate and computations it is possible to deduce the position of the zenith from its relationship to the known positions of identifiable stars in the photograph (see Fig. 1).

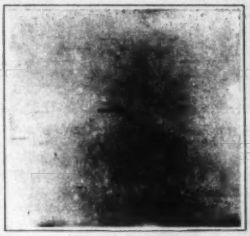

Fig. 1--Specimen record of photographic plate showing star-trails

Fig. 2--Camera and appurtenances

The camera-equipment (see Fig. 2) consists of three distinct items, namely, (1) zenith-camera (2) chrono-camera for recording the sidereal time of the exposures, and (3) control-box for operating the equipment. The zenith-camera rests on a heavy tripod which permits rotation about a vertical axis. The tripod may be leveled by means of small level-vials on the tripod-head. The camera-body has two ten-second level-bubbles and three leveling screws. After the camera is set up and properly leveled internal collimation is accomplished. The collimating-system (see Fig. 3) consists of an eyepiece, an illuminated reticle which is adjustable in the plane normal to the optical axis, two inclined mirrors, an objective lens, a large semi-transparent mirror, and a mercury pool. The system is so arranged that the image of the reticle is projected onto the surface of the

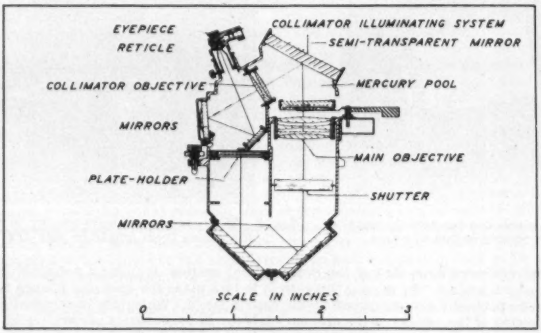

Fig. 3--Cross-section of zenith-camera, Type A-1

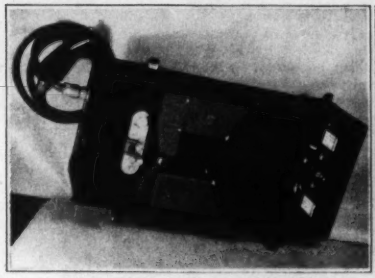

Fig. 4--35-mm fixed-focus camera to photograph simultaneously three sidereal watches

Fig. 5--Automatic operation by control-box

Fig. 6--Set-up of zenith-camera.

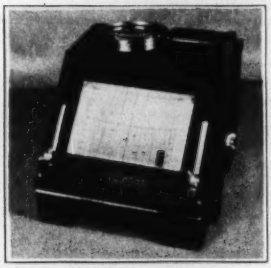

Fig. 7--Light-box for zenith-camera for identification of stars

Fig. 8--Microscope and micrometer to measure distances from zenith to star-trails

mercury pool and reflected back through the same optical system, forming a reflected image in the same plane as the reticle. By moving the reticle in this plane the operator causes the reflected image to be perfectly superimposed on the reticle itself. When this is accomplished the axis of the projection of the reticle on the mercury mirror is necessarily perpendicular to the horizontal surface of the mercury, or in other words truly vertical. By this means it is assured that the image of the collimator-reticle is projected toward the camera lens in a vertical line as

if it were coming directly from the true zenith overhead. When perfect collimation has been attained the mercury pool is moved out from its position above the camera objective and the camera is ready for use.

The main optical train consists of a 24-inch f/6 lens, a louvre shutter, two front-surfaced glass mirrors inclined at 45° to the optical axis, and a photographic plate, together with the semi-transparent mirror that is part of the collimating-system. When the shutter is opened star-trails are exposed on the plate together with the image of the reticle which, because of its prior collimation, represents the true position of the zenith among the stars. At the same time a data-card is exposed on the edge of the plate showing all pertinent data for identifying the plate.

The chrono-camera (see Fig. 4) contains a 35-mm fixed-focus camera which simultaneously photographs three sidereal watches at the mid-point of each automatic exposure of the zenith-camera. The mean of the three watch-readings, properly corrected for watch-error, represents the time of the exposure. For the purpose of calibrating the watches, the chrono-camera is also equipped with a trigger-release by which the three watches may be photographed at the instant of selected time-signals which may be received over the radio.

The control-box (see Fig. 5) is so designed that by depressing a single button the following operations automatically take place in proper sequence: (1) Zenith-camera shutter is opened for two seconds; (2) at the exact mid-point of this exposure the chrono-camera shutter is tripped; (3) the collimator-reticle is illuminated at a pre-determined intensity and exposed on the plate; (4) the data-card is illuminated and exposed for four seconds. At another setting on the control-box essentially the same sequence is followed except that the collimator-reticle and the data-card are not reexposed. The control-box also contains a battery, supply of plate-holders, fresh plates, developing-tank, and other accessories for operating the equipment. In addition to the automatic operation of the equipment by means of the control-box, the zenith-camera shutter may be operated manually by means of a cable-release which has a lock for keeping it open. The camera is equipped with a changing bag for loading and unloading the plates in the field and a light-proof developing-tank (see Fig. 6) so that the plates may be developed any place where there is adequate water-supply. Thus, there is no need for a dark-room or laboratory.

The present practice in the use of the camera involves essentially the following procedure. The tripod is set up and leveled by means of leveling screws at the base of the legs. The camera-body is then leveled by means of its three leveling-screws and the sensitive levels mounted on it. With the mercury pool in position over the objective, the camera is collimated. The mercury pool is then swung out of position and an automatic two-second exposure is made. After a pause of about ten seconds the shutter is opened manually to expose star-trails of about ten seconds' duration. The camera is then reversed 180°. It is releveled by means of the three leveling-screws on the camera-body, but instead of depending on the level-bubbles final leveling is checked through the collimator-system. During this releveling the reticle is not adjusted but is kept in its original position to avoid disturbance of the internal relationship of the optical parts. Another automatic two-second exposure is made on the same plate but this time the reticle and data-card are not re-exposed. After a pause of approximately ten seconds the shutter is operated manually to obtain either two short trails or one extra long trail. This change in the pattern of exposure makes it easy to distinguish between the exposures taken in the first and second positions.

It was first expected that the problem of identifying the stars on the plate would present difficulties to the inexperienced personnel who might be required to operate the camera. However, a system has been developed that makes this problem quite simple. A light-box (see Fig. 7) was constructed containing a glass window which is illuminated from behind by diffused light. Just behind the glass window there is a long strip of thin acetate mounted on two spools, so that any desired portion of the strip may be exposed in the window. On the strip is drawn a projection-grid of hour-circles and parallels of declination covering the full region from the equator to the pole, and to the same scale as the photographic plates. With the Greenwich sidereal time of any particular plate-exposure known from the chrono-camera record and the approximate longitude of the exposure-station known, the local sidereal time of the exposure can be readily determined. This is the right-ascension of the zenith. The approximate latitude of the station is the approximate declination of the zenith. With these data known, the plate is placed over the grid so that the zenith is properly located with respect to the right-ascension and declination lines of the grid. Orientation of the plate may be accomplished by placing the star-trails on the plate parallel to the parallels of declination on the grid. With the plate in its proper position, the right-ascension and declination of any star-trail may be read from the grid. With these data the stars are readily ident-

ified in the Boss General Catalogue of Stars for the Epoch 1950.

The next important step in reducing the plates is that of measuring the distances between zenith-mark and star-images on the plate. For this purpose a measuring engine (see Fig. 8) has been developed which will measure a single coordinate to one micron. The engine consists essentially of a fixed microscope under which there is a movable stage mounted on a precision-screw along which the measurements are made. The stage is so constructed that it may be rotated as desired. In practice the zenith-camera plate is placed on the stage with the zenith-mark centered on the center of rotation. In this position the radial distance from the zenith-mark to any star-trail may be measured. Each star-trail is measured first to the right of the zenith-mark, then to the left, and the mean of the two measurements is used for the computations.

The present method of computation is based on the principle of direction-cosines. The direction-cosines of each star are computed with respect to the axis of the Earth, an axis through the vernal equinox, and an axis perpendicular to the plane of these two. Then an expression is set up relating the known direction-cosines of each star, the unknown direction-cosines of the zenith-point, and the zenith-distance of the star as determined from plate-measurements. Since the expression contains three unknowns, three stars must be used in each exposure for the solution of simultaneous equations. If a solution is made for each exposure, that is, before and after reversal of the plate, and the direction-cosines determined from the two solutions, they may be reduced to latitude and longitude; and the mean of the two determinations represents the correct geographic position of the zenith. This reversal eliminates instrumental errors in collimating the camera and errors of centering the plate in the measuring engine. Present plans for the use of the camera contemplate that three stars will be measured and computed in a field - office before the plates are sent in. The final computation at the office will include all identifiable stars and will involve a least-squares solution.

Observations made with the zenith-camera to date at known astronomic stations indicate that latitudes may be determined consistently within an accuracy of two to three seconds of arc - one-second accuracy is not unusual. However, the accuracy of the longitude-determinations is a function of precise timing which is at present perhaps the weakest link in the whole process. Studies and experiments are still in progress to improve the accuracy of the timing either by means of better time-keepers or improved technique. Studies under way at present include experimentation with a new type of control-panel, attempts to replace the chrono-camera with a precision break-circuit chronometer (both with and without a chronograph), and attempts to hook up the camera-shutter so that it may be operated directly by the break-circuit chronometer through an electric relay. It is hoped that in the near future it will be possible to improve the accuracy of the timing to such an extent that latitudes and longitudes may be determined with equal fidelity.

U. S. Army Air Corps,

Washington, D. C.

GRAVITY OBSERVATIONS IN NORTHERN NEW ENGLAND

George P. Woollard

Introduction--Fifty-one new gravity stations were established by the writer in northern New England in 1943. The measurements were made with a Humble Oil Company "X"-type gravity meter set for an operating sensitivity of 0.3 milligals. The instrument was made available to the writer by the American Geophysical Union to whom it is on loan from the Humble Oil Company.

Location of stations--The stations were established at about six-mile intervals on a closed loop extending northward from Chelmsford, Massachusetts, to Nashua, New Hampshire, northeast to Freeport, Maine, northwest to Gorham, New Hampshire, west to Burlington, Vermont, south to Rutland, Vermont, east and southeast to Concord, New Hampshire, and south to Nashua.

Reduction of gravity values--The observed values of gravity at all stations were put on the absolute Potsdam basis by reoccupying gravity stations for which the absolute values of gravity were known. The stations used were Woods Hole, East Wareham, and Lexington, Massachusetts. All are gravity stations established by the writer with the same gravity meter in 1941. They were chosen since this particular group of stations had been tied in to some 30 odd pendulum gravity stations of the United States Coast and Geodetic Survey. An attempt to reoccupy the United States

Coast and Geodetic Survey pendulum-station at Nashua, New Hampshire, was not successful as it was not possible to reoccupy the site of the original station.

Drift-control--Experience with this instrument has shown that the drift is fairly linear and also that it averages less than one milligal a day. The procedure used in the field for determining accumulative drift was to reoccupy each morning the last station occupied the evening before and, on completing the loop, to reoccupy the first station and those base stations at Lexington, East Wareham, and Woods Hole which had also been occupied at the beginning of the survey. This gave four checks on the accumulative drift, and the amount indicated was distributed on the basis of the number of days involved and the overnight drift-determinations. The probable error introduced by

Fig. 1--Map showing locations of reoccupied and new gravity-stations

this method of considering the drift of the instrument is believed to be less than 0.5 milligal.

Station elevations--Elevations were determined from United States Geological Survey topographic sheets, and the Dictionary of Altitudes [see 1 of "References" at end of paper].

Geographic control--All stations were located either at road intersections or railway depots. This system had two advantages, namely, these locations gave points easy to spot for future reoccupations and these locations were most apt to have elevation-data available. The actual geographic coordinates were taken off the topographic sheets of the United States Geological Survey.

Gravity anomalies--The data were corrected for the theoretical value of gravity based on the International formula, the elevation of the station above sea-level, and the mass-distribution above

sea-level using an average density-value of 2.67. The resulting simple BOUGUER anomalies, plotted and contoured, are shown in Figure 2. No attempt was made to make a terrane correction since for this type of survey the labor required is not justified. The probable average error introduced for neglecting terrane in this area is between 0.5 and 0.7 milligal with a probable maximum error of perhaps two milligals in those areas with the most rugged topography.

Results of survey--In order to show the degree of continuity in the gravity field between northern and southern New England, Figure 2 is a plot of the BOUGUER anomaly values for both areas. The new stations are shown as circles and the adjacent pendulum stations as dots. Stations in southern New England have been omitted for the sake of clarity. Those interested in the station distribution in this area are referred to LONGWELL [2].

There are two features which are continuous from southern New England into northern New England. One of these is the area characterized by very low gravity values which parallels the Hudson River Valley and Lake Champlain, and the other is the parallel area of higher gravity values just east of the New York State-Line. In connection with the first, it will be noticed that this feature more or less pinches out at about the junction of the New York-Vermont State-Line and the Canadian Boundary. That this is not the termination of the gravity trough though is indicated by a gravity traverse established by the Dominion Observatory in Canada. This traverse, off the map of Figure 2, shows a strong gravity minimum southeast of Quebec. This pinching out of the gravity trough has also been observed at other localities. A notable instance is near Harrisburg, Pennsylvania, where the "Blue Ridge Low"--the southern extension of the "Hudson River Valley Low"--is pinched out in a similar manner [3]. It would thus appear that the characteristic form of this rather narrow but long area of low gravity values which extends from Alabama to the Gulf of the St. Lawrence is a series of connected "lows" rather than a continuous belt.

The area of positive gravity values which parallels the above gravity trough in southern New England extends practically to the Canadian Border. It will be noticed though that the sign of the anomaly in northern New England becomes increasingly negative and the amplitude of the "high" correspondingly less the further north one goes.

The strong gravity "high" found on Cape Anne which apparently carries to the south across Cape Cod and Martha's Vineyard terminates at about the Massachusetts-New Hampshire State-Line. The traverse made to intercept it in southern New Hampshire showed anomalies varying from +1 to +14 milligals in contrast to the +44 milligals noted to the south. A similar attempt to trace its northward extension magnetically showed only 60-gamma variation, whereas a magnetic profile on Cape Cod over the gravity maximum showed a magnetic anomaly of over 2000 gammas.

Of the features present in northern New England that are not present in southern New England, the most pronounced is the large area of low gravity values which is found in central New Hampshire. The periphery of this area extends all the way to the coast on the east and to the gravity ridge mentioned above on the west.

Significance of the gravity anomalies--If the above delineation of the gravity anomaly areas is considered along with the two profiles shown in Figure 2, it is found that northern New England presents a rather unique group of gravity relations.

Considering first the area of low gravity values in central New Hampshire, this is the area of the White Mountains, and the gravity "low" apparently indicates a sub-crustal "root" of material of lower density than that on each side of the mountains. This is the normal relationship observed over most mountains.

In connection with the gravity "high" paralleling the New York-Vermont State-Line, it is seen that the axis of this high coincides with the axis of the Green Mountains. In this case there is no indication of a "root" beneath the Green Mountains but rather evidence of high-density rocks totally uncompensated and the whole area out of isostatic equilibrium.

The explanation of this difference in the gravitational reflection of two mountain ranges in the same general area can not be attributed to the surface rocks since the density-difference between the two is relatively slight. The rocks in the White Mountains are predominantly metamorphic schists and granites with an average density of about 2.7. The rocks in the Green Mountains are metamorphic gneisses of varying composition whose density varies from about 2.7 to over 3.0 with an average value of about 2.8.

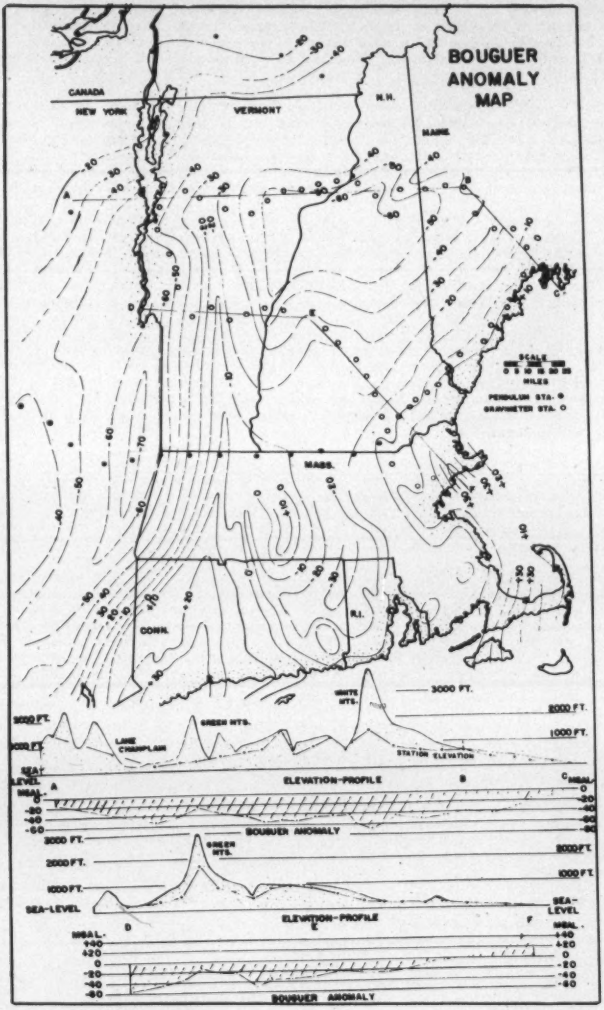

Fig. 2--Bouguer anomalies and contours

That the relation can not be explained on the basis that the Green Mountains is an overthrust-sheet of high-density rocks without a "root" is also obvious from the above density-values. Even on the basis that hornblende gneisses predominated and that the average density was about 3.0, rather than 2.67 as used in the reductions, the effect on the anomaly would not amount to more than about ten milligals.

It therefore appears to be a coincidence that the gravity "high" lies along the axis of the Green Mountains, and the real cause of the anomaly is the sub-crustal mass-distribution. This explanation is plausible since as indicated earlier, the gravity "high", as well as the parallel gravity "low", extends the entire length of the eastern seaboard. Sometimes the axis of the "high" coincides with outcrops of metamorphic gneisses as in New England and at Wilmington (Delaware) and sometimes it occurs over outcrops of rocks with less density, as granite at Washington, D. C.

Similarly an examination of the regional relations between the geology and the axis of the gravity "low" indicates that it is not confined to any type of surface lithology. In Virginia the axis lies along the Blue Ridge Mountains. In New England the axis occurs in the Hudson River and Champlain valleys. The only general geologic correlation that can be made is that both the gravity "high" and "low" parallel the structural trend of the Appalachian Mountain System and that the "low" follows rather closely the zone of overthrusts on the east side of the postulated Appalachian geosyncline.

LONGWELL [2] has interpreted these major gravitational features as representing crustal "warps". That is, the regional gravity anomalies reflect the configuration of the bottom of the granitic crust and the sign and magnitude of the anomaly is a reflection of the thickness of the crust. Areas with strong positive anomalies are areas where dense sub-stratum material approaches the surface. Areas with marked negative anomalies are where there is an extra thickness of the less-dense crustal material.

In his study of the gravity relations in southern New England, LONGWELL [2] concluded that the Hudson River Valley "low" and the "low" observed in the Rhode Island Basin were probably reflections of "downward bulges at the base of the sial shell formed during the Paleozoic history of subsidence and mountain building." The "high"-gravity anomaly area in between being an area of crustal thinning characterized by uplift. (This is the approximate location of the axis of the Triassic Arch, and this relation appears to be maintained throughout the eastern seaboard.)

The above interpretation of the regional anomalies is believed to also apply to northern New England. Therefore the areas of positive and negative anomaly are interpreted as representing areas where the crust thins and thickens. Similarly changes along any axis, as the change from +34 milligals in southern New England to -24 milligals in northern New England on the positive axis represents a change in crustal thickness. So although the Rhode Island Basin and the White Mountains are indicated by the gravity contours as being part of the same orogenic province, the amount of crustal deformation persisting varies as shown by the gravity values, namely, -30 to -60 milligals. If the gravity-"ridge" values reflect the degree of arching in Mesozoic time that gave rise to the present Triassic troughs, then the change from strong values in southern New England to weak ones in northern New England indicates that there was little arching in this area compared to that which took place further south. This relation may reflect the presence of the Adirondack massif which flanks the area on the west side.

Residual-gravity anomalies--Although no attempt was made to systematically determine the relation between residual anomalies and surface geologic features, it is obvious from the two profiles shown in Figure 2 that a positive residual would be obtained in the Green Mountain Area. The size of the anomaly indicated on both profiles is about ten milligals, and this value is in fair agreement with the known density-values in the area.

Editor's note--Since completing this paper the author has established about 75 more stations in New England and has cooperated with the Dominion Observatory in establishing about 500 new stations in the Maritime provinces. The only gap now remaining is in Maine.

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[1] Dictionary of altitudes, U. S. Geol. Surv. Bull. No. 274.
[2] C. R. LONGWELL, Bull. Geol. Soc. Amer., v.54, pp. 555-590, April, 1943.
[3] G. P. WOOLLARD, Bull. Geol. Soc. Amer., v.54, pp. 791-818, June 1, 1943.

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PROGRESS OF THE GEODETIC AND TOPOGRAPHIC WORK IN MEXICO, FROM MARCH, 1943, TO DATE

Manuel Medina

(1) Triangulation-projects:

The triangulation-projects begun in 1943 and finished wholly or in part to date are the following:
(a) Topographic triangulation in the vicinity of the Nevado of Colima (snow-capped peak of Colima).
(b) Geodetic triangulation covering the State of Colima.

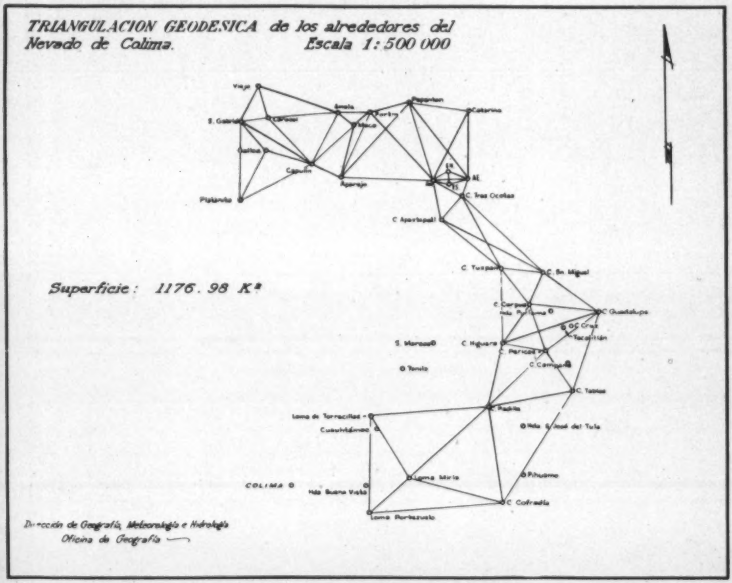

Fig. 1--Triangulation in region of Colima

(c) Geodetic triangulation along a part of the 19th parallel (between Puebla and Veracruz).
(d) Geodetic triangulation along the 26th parallel (between the 98th and 103rd meridians).

(a) The topographic triangulation in the vicinity of Colima (see Fig. 1) covers an area of 1176.98 square km and had for its purpose the establishment of points of topographic control in the vicinity of the above-mentioned height (4,650 meters) for the support of a survey of the vicinity by aerial photography. It was composed of 30 vertices, at which observations were made with a precise Wild theodolite, making 12 pointings or sights at each vertex in the two positions of the instrument. It was dependent on a topographic base measured with a 50-meter invar tape and connected to the triangulation of Colima at one of its geodetic vertices.

(b) The geodetic triangulation of the State of Colima (see Fig. 2) forms part of the general arc projected along the 104th meridian (west of Greenwich) and depends directly on the triangulation of Jalisco which is already computed and adjusted. Three quadrilaterals with a central-point cover almost all the surface area of the State. The observations were made with a "Wild" theodolite on

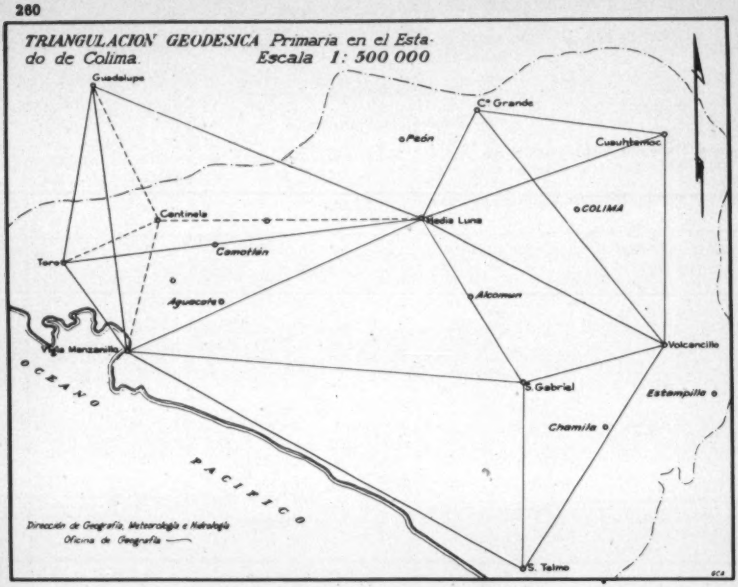

Fig. 2--Triangulation of State of Colima

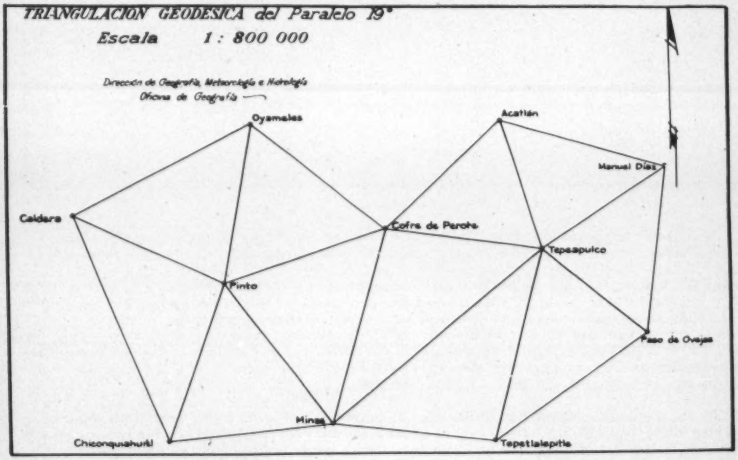

Fig. 3--Triangulation of 19th parallel

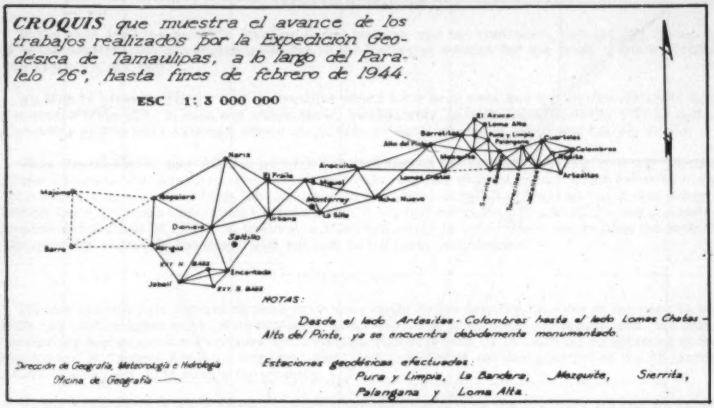

Fig. 4--Triangulation of 26th parallel

which it is possible to estimate the readings to 0".2 on both circles, taking 24 sights at each vertex. All the observations were made at night using a signal-lamp designed by the Chief of the Party in view of the fact that it was impossible to obtain special lamps with concentrated filaments, since they are at present non-existent in the markets of the country.

(c) The triangulation of the 19th parallel (see Fig. 3) becomes practically a prolongation to the east of the arc which extends from the 98th meridian across the Valley of Mexico and continues by way of the Lerma and Santiago rivers to the State of Sinaloa. It consists of a pentagon and a hexagon which cover a surface area of 7339.52 square km. The angle-observations were made using a "Wild" theodolite on which it is possible to estimate the readings to 0".2 on both circles, the observations having been notoriously difficult and prolonged at some stations due to the clouds that cover, for long periods of time, the peaks of the range of the Sierra Oriental, in the vicinity of the sea.

The geodetic triangulation of the 26th parallel (see Fig. 4) departs from the side Artesitas-Colombres which belongs to the last figure, to the north of the arc of the 98°-meridian (west of Greenwich). At present, the reconnaissance has been completely accomplished up to its connection with the triangulation of La Laguna, and a geodetic party (brigade) is making angle-observations using a Repsold and Son altazimuth on which it is possible to estimate the readings to 2" on both circles. In the level region of this triangulation steel-towers 14 meters in height are used for the observations, as well as ordinary gasoline lamps of 500-candle light, instead of electric lamps.

The schematic Figures 1 to 4 show the development of the above triangulation the results of which may be summarized as follows:

Item	Square km
Geodetic triangulations finished before 1943	205,900
Triangulations finished from January 1943 to date	13,242
Total of triangulations	219,142
Triangulation in preparation (reconnoitred)	56,507

(2) Points of topographic control

For the purpose of making the survey of the first-order roads of the country and of placing along them sufficient points of control that could be identified from the aerial photographs, the topographic survey was made, from those existing in the States of Jalisco, Puebla, and Tamaulipas, by extending the surveys to the terminal points. In this manner numerous points of control were located along each road (with an approximate spacing of five km one from another) and were marked

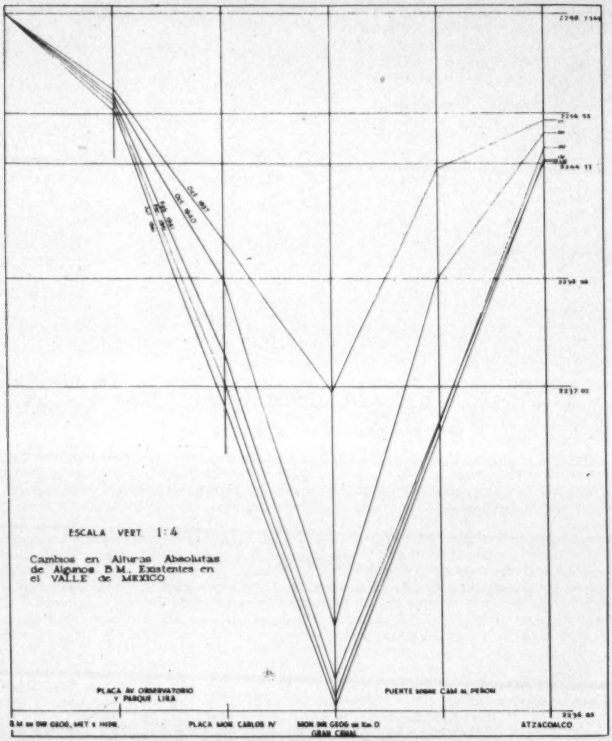
ESCALA VERT. 1:4
Cambios en Alturas Absolutas de Algunos B.M. Existentes en el VALLE de MEXICO
PLACA AV. OBSERVATORIO Y PARQUE LIRA
PLACA MON. CARLOS IV
PUENTE SOBRE CAM. AL PERON
ATZACOALCO
GRAN CANAL

Fig. 5--Leveling executed from 1937 to 1943

by means of a small concrete structure and with a regulation bronze-plaque. The longitudes and latitudes of these points were computed with reference to the geodetic coordinates of the vertices of the neighboring triangulation.

(3) Astronomy of position

To aid the survey by aerial photography of the State of Tabasco, some astronomic positions were determined in that State, using instruments and methods of observation adequate for determining latitudes and longitudes with error of less than 5″, which approximately represents the value of the deviation of the vertical in that zone. Considering the nature of the topography of the region, sensibly horizontal, covered with vegetation and with communication only by river, the establishment of a stronger control is difficult and at present not economical, the determination being good enough for the cartographic needs of the moment, that is for scales of 1:200,000 or greater.

(4) Precise leveling

In the year 1943 the geodetic leveling in the country was not continued, this activity being limited to the development of various levelings in the Valley of Mexico for the study of the movements of the subsoil of the city.

An idea is given in Figure 5 of the results which have been obtained during the different leveling executed from 1937 to date and which show, indisputably, that the subsoil of the City is suffering sensibly appreciable sinkings whose magnitude in some places is about one cm per month.

This circumstance may explain perhaps the fact that in the precise leveling recently executed between Tacubaya and Acapulco, the latter place was reached with a closure which differed in the neighborhood of five meters from that obtained in the above-mentioned Port by the direct determination from the mean sea-level; assuming that it started from the altitude of the bench-mark of Tacubaya determined in 1913. At present, a thorough study is being made concerning the stability of the geodetic vertex of Tacubaya with respect to its three coordinates.

(5) Gravimetry

No new gravimetric determinations have been made in the country, in view of the need to intensify the cartographic work. Nevertheless, with respect to gravimetric computations, the computations for topographic corrections and isostatic compensation of 25 stations established in the Republic and in Central America were finished, thus completing the computation of the 68 gravity stations determined up to now in the country.

These computations were made applying a process devised by the Engineer RICARDO TOSCANO whose results do not differ practically from those obtained by the method of the United States Coast and Geodetic Survey, introducing on the other hand some simplifications.

In order that these results by both methods may be compared, some of the values are given below:

Corrections for topography and isostasy in milligals at various stations in Mexico by the methods of the United States Coast and Geodetic Survey and of Engineer Toscano

Station	C. G. Survey		Toscano	
	Bowie	Intern.	Bowie	Intern.
Tapachula, Chiapas	-17	-27	-18	-28
Tuxtla Gutierrez, Chiapas	-48	-58	-48	-58
Tonala, Chiapas	-41	-51	-36	-46
Viesca, Coahuila	1	- 8	2	- 9
Durango, Durango	-51	-61	-50	-60
Monterrey, Nuevo Leon	10	0	7	- 3
Oaxaca, Oaxaca	-45	-55	-44	-54
Matias Romero, Oaxaca	16	6	15	5

(6) Cartography

The compiling and publication was completed of an atlas of geographic charts of the Republic in the scale of 1:500,000, on sheets covering 3° of longitude by 2° of latitude. Each one of these sheets contains approximately an area of 70,000 square km and are constructed according to the "Lallemand" polyconic projection. This atlas is projected and constructed in such a way that upon the joining of four adjacent sheets and reducing in proportion, one would obtain maps in the scale of 1:1,000,000 by means of which our Republic, according to International agreement, should be able to do its part in the formation of the world map in the scale of 1:1,000,000.

Oficina de Geografia,
Tacubaya, D. F., Mexico.

AMERICAN GEOPHYSICAL UNION

TWENTY-FIFTH ANNUAL MEETING

SECTION OF SEISMOLOGY

EASTERN SECTION OF SEISMOLOGICAL SOCIETY OF AMERICA

REPORTS AND PAPERS

Washington, D. C.
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PROGRESS-REPORT OF THE JESUIT SEISMOLOGICAL ASSOCIATION FOR THE YEARS 1941, 1942, AND 1943

James B. Macelwane

The tripartite arrangement between Science Service, the United States Coast and Geodetic Survey, and the Jesuit Seismological Association has continued in fruitful operation during these years in spite of the difficult circumstances created by the war. Through this arrangement, telegraphic reports are received from important stations in the United States so that immediate determinations of the epicenters of earthquakes can be made independently by the United States Coast and Geodetic Survey in Washington and the Central Station of the Jesuit Seismological Association in Saint Louis. In addition to this excellent arrangement, the United States Coast and Geodetic Survey has made available by mail to the Central Station of the Jesuit Seismological Association in Saint Louis information on earthquakes transmitted through courtesy of the State, War, and Navy Departments from such stations in the Pacific Area as Fairbanks and Sitka (Alaska), Honolulu (Territory of Hawaii), Brisbane, Perth, and Riverview (Australia), Wellington (New Zealand), Apia (Samoa), and Balboa Heights (Canal Zone). In addition to these, reports are received by mail from Tacubaya (Mexico) and from Bogota (Colombia), and through the courtesy of the Carnegie Institution of Washington readings are also obtained from the seismograms of the station at Huancayo (Peru).

This would seem to be a large spread of reporting stations; but it is found quite often that the data thus assembled are entirely inadequate for a satisfactory location of the earthquake-epicenter. If the plans for expansion of seismological services in Middle and South America bear fruit, the location of epicenters will be much improved.

The Central Station of the Jesuit Seismological Association made 74 locations of epicenters in the year 1941, 58 in 1942, and 45 in 1943 (see Fig. 1). The great majority of these epicenters lie around the rim of the Pacific Ocean. None was very deep. The three-year maximum depth of 300 km was reached in one earthquake near the Fiji Islands and in another in the Bolivian Andes. Nearly all the major earthquakes on the West Coast of South America were deeper than normal. This is true also of many of the earthquakes on the Pacific Coast of Central America and western Mexico--many of the depths ranging between 100 and 200 km. An earthquake with a depth of 150 km occurred off the Alaskan Peninsula and another with a depth of 250 km took place on the mid-Atlantic swell, a few degrees north of the Equator.

Preliminary Bulletins were published on each of these earthquakes and were distributed to stations within the territories of the Allied Nations. In the hope that exchange relations will be restored when peace comes, copies of all these Preliminary Bulletins are being reserved for later distribution to stations in other areas.

The work of the Central Station has been much restricted and delayed through the loss of personnel to the armed forces. It has been found impossible to secure suitable appointees for graduate fellowships and assistantships. In addition, the senior personnel has been overloaded with war work, particularly with the teaching of physics and mathematics in the Army Air Force Radio Instructors School and to the enlisted men in the Army Special Training Program. It is hoped that the present summer will permit more rapid progress.

Nearly all of the stations of the Jesuit Seismological Association have been active during this three-year period; but a number of them have not been able to publish reports except in so far as their data were utilized in the Preliminary Bulletins of the Central Station. The one station of the Association which has made a remarkable record in keeping its bulletins up to date is Santa Clara, under the direction of Reverend JOHN A. WEBER, S.J. A very particular mention should be made of Father A. W. FORSTALL, S.J., the veteran Director of the Regis College Station in Denver, who in spite of his eighty-five years has, single-handed, kept his station in continuous operation. No new stations were established during these years, but the equipment at Spring Hill and at Saint Louis has been improved.

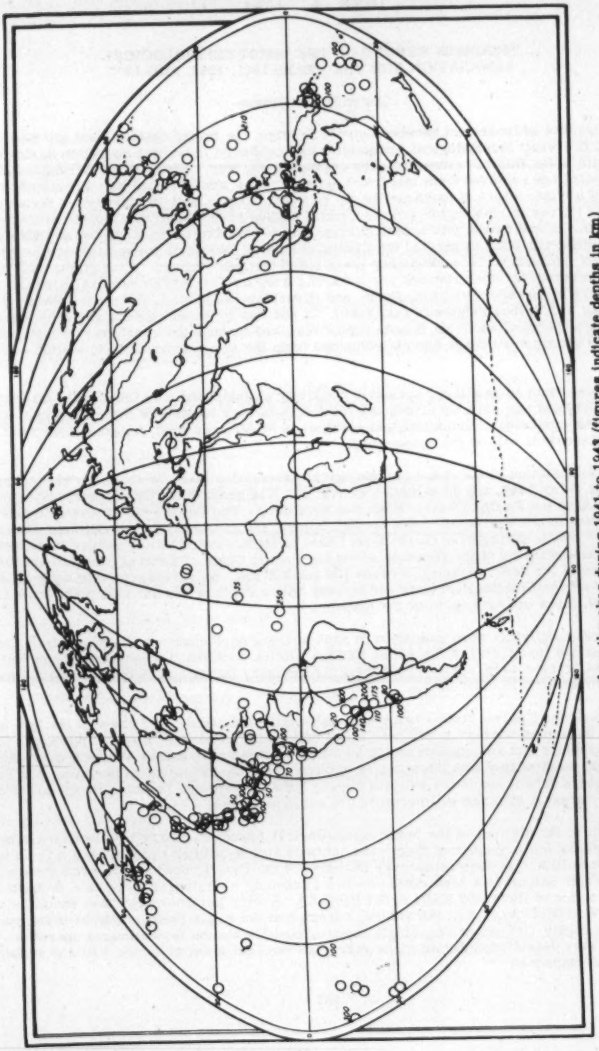

Fig. 1--Epicenters of earthquakes during 1941 to 1943 (figures indicate depths in km)

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PROGRESS-REPORT ON SEISMOLOGICAL ACTIVITIES OF THE UNITED STATES COAST AND GEODETIC SURVEY

Ralph R. Bodle

Seismological work of the United States Coast and Geodetic Survey continued with little interruption, though difficulty of operation increased in some instances due to war conditions.

Teleseismic work--The Survey continued to publish teleseismic data for 23 stations. All but four of these were operated on a cooperative basis. Their continuance in service in many instances is worthy of special appreciation on the part of seismologists. A note of appreciation is due the Department of Terrestrial Magnetism of the Carnegie Institution of Washington for making personnel available to continue operation of the station at College, Alaska, when personnel from the University were no longer available. Several University and College stations have continued to operate while engaged on unusually heavy teaching programs.

One new station was established during the year (August, 1943) through cooperation with the South Dakota State School of Mines and Technology at Rapid City. Professor EDWARD L. TULLIS of the Department of Geology is in charge. The equipment is a remodeled single-component Wood-Anderson seismometer oriented to record east-west motion. It has a static magnification of approximately 580 and a pendulum period of five seconds. The seismometer was loaned by the Seismological Laboratory at Pasadena, while the recorder, program-clock, and radio for time-signals were furnished by the United States Coast and Geodetic Survey.

Arrangements have been made to publish data from a private station at New Kensington, Pennsylvania, operated by FRED KELLER. The instrument is a long-period horizontal seismometer of special design connected to a long-period galvanometer. The record is made on smoked paper using a photocell pick-up, electronic amplifier, and electrical recorder. It is understood that this station has been in operation for more than a year without need for repairs. The orientation is north 15° west to south 15° east. Magnification is about 500, but can be varied over a rather wide range. Some of the results from this station have been published in the Seismological Bulletin of the University of Pittsburgh, but issuance of this Bulletin has been temporarily suspended.

All records of the Bermuda Seismograph Station have now been transferred to the Survey, where they will be filed until after the present emergency.

Records from Ivigtut and Scoresbysund, Greenland, continue to come to the Survey for temporary filing. They are being interpreted and the data included in the Seismological Bulletin. The Survey continues to furnish supplies for the Greenland stations.

Exchange of teleseismic data for all important Mexican shocks continued with the seismological station at Tacubaya.

Preliminary determination-of-epicenter cards were issued for 40 earthquakes on the basis of telegraphic data received through Science Service, the Jesuit Seismological Association, and other cooperating agencies.

Data from the new Chinese station of the National Geological Survey of China at Pehpei, near Chungking, were received through Science Service. Arrangements have been made to duplicate their data and distribute them to interested seismologists.

S. P. LEE, formerly in charge of the Chiufeng Station, operates the new one which he built using locally available material. The original station is now in territory occupied by the Japanese. Mr. LEE is well prepared to build and operate a seismograph, as he has studied seismology both in this country and in Europe. There has been some difficulty in obtaining satisfactory time-control.

Recording of local and regional earthquakes, in cooperation with the United States Bureau of Reclamation, continued in the region of Lake Mead, Shasta, and Grand Coulee dams. This work was carried on by a special party with headquarters at Boulder City, Nevada. Aside from the purely local objectives of this work the data recorded for shocks outside the immediate regions of the stations is proving of considerable value. The records of the Mt. Lassen Station, a subsidiary of the University of California Seismological Station, are being made available for correlation with data from this group of stations. The party maintains its own service for collecting felt reports in the region of Lake Mead.

At the close of the period covered by this report the Seismological Bulletins issued by the bureau had been distributed through June, 1942. The third quarter of the same year was about to be mailed. This represents a reduction during the year of between five and six months in the period between production of the records and publication of the data. Progress on this item, however, was obtained at the expense of other work, so it can not be expected to continue at the same rate.

Earthquake-information service--The program for collecting felt reports continued. Collection of these data on the Pacific Coast and in the Western Mountain Region was done by the Seismological Field Survey with headquarters in San Francisco. That Office had the assistance of some 40,000 cooperators and the active collaboration for various purposes of a number of representatives throughout the region who hold official appointments as "Collaborators" or "Consultants in seismology" as follows: Dr. Hugo Benioff, Pasadena, California; Dr. Perry Byerly, Berkeley, California; Prof. R. R. Martel, Pasadena, California; Prof. Vincent P. Gianella, Reno, Nevada; Prof. J. Stewart Williams, Logan, Utah; Prof. Arthur J. M. Johnson, Bozeman, Montana; Dr. Francis A. Thompson, Butte, Montana; Rev. B. J. Topel, Helena, Montana; Dr. Gordon M. Butler, Tucson, Arizona; Dr. Harold E. Culver, Pullman, Washington; Dr. J. Donald Forrester, Moscow, Idaho; Prof. C. A. Heiland, Golden, Colorado; Dr. Earl L. Packard, Corvallis, Oregon; Prof. Stuart A. Northrop, Albuquerque, New Mexico.

In the Central States collection of felt data was facilitated by cooperation of the Jesuit Seismological Association headed by Rev. JAMES B. MACELWANE, S.J., in Saint Louis. Similar service was performed in the Eastern States by the Northeastern Seismological Association, where Rev. DANIEL LINEHAN, S.J., at Weston, Massachusetts, has been active in collaboration with the Dominion Observatory at Ottawa and the Harvard Seismograph Station.

There were no outstanding earthquakes during the year, though 12 were strong enough to require intensive coverage by questionnaire. In California and the Western Mountain States the principal shocks of near-destructive intensity occurred on August 28 in southern California and October 25 in central California. Both were well recorded on strong-motion instruments, but only the latter produced records of sufficient amplitude to require analysis by integration. This work is now in progress.

Strong-motion work--The 53 strong-motion stations of the Survey and cooperating agencies continued in operation, though the equipment of two stations was reduced by transfer of the accelerographs to another project. It is expected that they will be replaced with new equipment as soon as the contract for replacements is completed. As mentioned last year, no instrumental development is being done by the Seismological Field Survey, though an experimental mechanical-vibration-recorder previously developed has now been installed at the University of San Francisco. Thirty-four strong-motion records were obtained from six shocks. The program of reducing the accelerograph-sensitivity at certain stations was extended to a few additional stations. This had been found desirable in order to increase the probability of recording the full ranges of motion likely to be encountered at stations which are located on other than rock-foundations and in the upper floors of tall buildings.

Period-amplitude envelopes for a number of strong-motion records of past years were prepared and will be published.

The quarterly progress-reports on strong-motion work were issued without undue delay.

Vibration-work was limited somewhat in comparison with previous years. Five building observations were made in addition to two series of observations made to determine the effect of vibrations caused by heavy machinery. Another series of observations was made to determine the stability of the seismograph-station site near Ukiah, California. Some vibration-observations were made in connection with national-defense projects.

Instrument work--The Neumann-Labarre vibration-meter has been remodeled to give a wider range to the period- and magnification-adjustments. The instrument will now have an increased range of usefulness both as a vibration-meter and as a short-period, high-magnification seismometer. Two units of the new model have been completed, and six more are under construction.

Clocks used at the seismograph-stations for time-marking purposes are being equipped with invar pendulum staffs. This will improve the clock-rates as the lengths of the old wooden pendulum staffs changed slightly with variable weather-conditions.

At some of the recording stations where the commercial power-service is subject to failure, electronic converters have been installed for use in emergency. They are arranged so that in case the normal power-service fails the operation of the seismograph is automatically switched to a storage-battery furnishing power through the converter which changes 12-volt direct current to 110-volt alternating current with an output of about 100 watts.

A number of recorders have been equipped with special lamps, time-marking devices, and synchronous motors.

It will be of interest to note that the Wenner seismometers at San Juan have continued to operate with little or no difficulty since they were placed under hermetically sealed covers in February, 1941, to keep out excessive moisture.

General--The Ground-Water Division of the United States Geological Survey continued to furnish reports on well-water fluctuations due to earthquakes. These reports will be published in the annual publication of the Survey.

A joint project sponsored by the United States Department of State and the United States Coast and Geodetic Survey was begun in South America. F. P. ULRICH, Chief of the Seismological Field Survey in California, went to South America to develop greater cooperation in the Western Hemisphere for the study of earthquakes. A modern accelerograph has been installed at Santiago, Chile, and another is ready for installation at Lima, Peru. Complete details on this project are not available, as it is still in a formulative stage. The itinerary had been only partially covered on April 1. Results obtained at that time were very encouraging and gave promise of a continuing optimistic trend. Colombia, Venezuela, and Chile had been visited by the end of March.

An experimental seismograph-station was operated for about three weeks at Uruapan, Mexico, in June and July, 1943, in connection with studies of Parícutin Volcano. The volcanic disturbances were apparently too superficial to transmit vibrations to this station some 15 miles away.

U. S. Coast and Geodetic Survey,
Washington, D. C.

A COOPERATIVE SEISMOLOGICAL PROGRAM WITH SOUTH AND CENTRAL AMERICA

Franklin P. Ulrich

In trying to set up a cooperative seismological program with South and Central America, a general outline of desirable seismological work was adopted similar to the program being carried on by the Seismological Field Survey of the United States Coast and Geodetic Survey in the Western United States. The purpose of my recent trip to these countries was to find out what seismological work is being done there; how the work could be incorporated and coordinated into a general program for the Western Hemisphere.

In discussing the program of the Seismological Field Survey with representatives of these countries, an explanation was given showing the economic value as well as the scientific value of each item of the program. A review or summary of those individual items will give a good picture of what work is being done in each country and also of what the general outline consists.

In the economic development of a country, the engineer or the planner must have complete information of the natural forces he will encounter in that development. Of these natural forces, earthquakes (particularly their intensities, frequency, and geographical distribution) are very important, especially in South and Central America where earthquakes have been very destructive. For that reason, a complete seismological history is needed in each country. In none of the countries visited was there a complete published history, although the information is completely available in some countries and partially available in the others. Work will be started in each country in the immediate future on compiling earthquake-history as one of the first steps in this coordinated program.

In order to keep the historical record up to date, the program calls for reports of current earthquakes through a questionnaire-program. Only Chile and Ecuador have such a program under way, each with about 200 voluntary reporters. The other countries also expect to get this part of the work started in the near future.

Detailed reports of major earthquakes with pictures of structural damage and changes in the Earth's surface are important to engineers and geologists. Chile, Ecuador, El Salvador, and Peru have covered this field fairly well. In Colombia and Venezuela some major shocks have been reported quite well. Costa Rica, Guatemala, and Panama had no plans for preparing such a report.

The need for maps, and especially fault-maps, cannot be overstressed in any engineering development. Several examples might be quoted showing the value of fault-maps and fault-locations.

A T L A N T I C
O C E A N
COLOMBIA
BRAZIL
BOLIVIA
COOPERATIVE SEISMOLOGICAL WORK IN AMERICAN REPUBLICS
COUNTRIES VISITED IN 1944: CHILE, PERU, ECUADOR, COLOMBIA, VENEZUELA, PANAMA, COSTA RICA, EL SALVADOR, GUATEMALA
STATIONS IN OPERATION
PROPOSED NEW STATIONS
A ACCELEROGRAPHS INSTALLED IN 1944

Fig. 1--Cooperative seismological work in American Republics

One of the reasons why Boulder Dam was placed in Black Canyon and not in Boulder Canyon was because geological conditions were better in Black Canyon. Morris Dam near Pasadena, California, was designed so that horizontal movement of parts of the dam could take place along the apparently dead fault which passes through the foundation of the dam. None of the countries visited has complete fault-maps. Costa Rica, Ecuador, Panama, and Peru have fault-maps for limited areas while the other countries have none whatever.

One of the chief goals of all earthquake-research should be to reduce loss of life and damage

to property at the time of an earthquake. In general these losses are due to inadequate design of buildings. Buildings can be designed and built to withstand earthquake-forces, but in general they are not built that way unless there is an adequate and well-enforced code of building. At the present time Chile and El Salvador have building-codes apparently to take care of future construction only. Various degrees of earthquake-resistant construction are required by building-codes in Costa Rica, Ecuador, Guatemala, and Panama. There is no requirement for earthquake-resistant design in Peru, and I am not sure about Colombia and Venezuela.

In order to measure the forces [period of vibration and amplitude of motion of large earthquakes (the type of information needed by engineers and architects to design earthquake-resistant buildings)] it is necessary to operate accelerographs. Two accelerographs were installed in South America during the recent trip--one at Lima, Peru, and the other at Santiago, Chile. Additional accelerographs should be installed at Cumana (Venezuela), Bogota (Colombia), Guayaquil (Ecuador) and Guatemala City (Guatemala). Information obtained with these instruments will be as valuable to engineers in the United States and other countries as to engineers in each of those particular countries.

In order to accurately locate the epicenters of earthquakes, and particularly the smaller ones which are not generally reported and which may be important in the seismological picture, it is necessary to set up and operate sensitive seismographs. In Venezuela an old-type sensitive seismograph is in operation at Caracas. Plans were discussed for adding two more sensitive seismograph stations in Venezuela at Cumana and Merida. At Bogota, Colombia, a very good vertical component and two old-type horizontal components are in operation with two horizontal-component instruments ordered and not yet delivered. It would be desirable to install three more sensitive seismographs in Colombia, at Baranquilla, Medellin, and Pasto. In Peru the Carnegie Institution of Washington operates a first-class station at Huancayo and the Peruvian Government is operating an obsolete instrument at Lima. The reorganization of the Seismological Bureau in Peru is under way and the plans call for setting up sensitive seismographs at Piura, Pozuzo, Lima, Nazca, and Arequipa. At the present time several seismographs are located at Quito, Ecuador, and it is proposed to set up additional instruments in Ecuador, at Manta and Shell-Mera, the latter being east of the Andes Cordillera.

In Chile, the Smithsonian Institution operates a fairly good seismograph at Calama, and the Chilean Government operates several old-type seismographs at Santiago. Twelve new Bosch-Omori sensitive seismographs have been constructed during the past year. New instruments will be installed during 1944 at Copiapo and Concepcion, and at Puerto Montt and Juan Fernandez Island during 1945.

In Central America, the United States operates two good sensitive instruments and an accelerograph at Balboa Heights. Costa Rica operates an obsolete instrument at San Jose. Old-type instruments are in operation at Salvador and Guatemala. It has been proposed to establish a new sensitive seismograph-station at David (west Panama) and to install modern instruments at San Jose, San Salvador, and Guatemala City. Figure 1 shows the present and proposed new stations.

It has been proposed that a central agency be set up to collect, interpret, and distribute seismological information. For the present all of the national representatives are in favor of accepting the offer of handling the work temporarily at Mexico City by the Pan-American Institute of Geography and History. A number of the national representatives have expressed a desire for a separate Pan-American Institute of Seismology with regular meetings of the national representatives.

My trip did not take me to Brazil, Bolivia, and Argentina, but Dr. GREVE of Chile has volunteered to contact these countries and ask their participation and cooperation in this seismological program.

In each of the last six countries visited, the representative of the country has requested and cooperated in preparing recommendations for a seismological program in that country. The program provides for starting at once with those items which require little or no initial expense but which do require some planning. The entire program might well be summarized as follows:

(1) Set up an adequate and responsible bureau for seismological work.
(2) Compile and publish a complete seismological history.
(3) Establish an earthquake-questionnaire program to obtain complete information on current earthquakes.
(4) Set up an organization and plan for a report of a major earthquake.

(5) Appoint a group or committee to study building-codes for earthquake-resistant design and then prepare and adopt a building-code which best meets local conditions in each country.
(6) Arrange for cooperative interchange of information and ideas so all countries can benefit by the work in other countries.
(7) Set up adequate seismological instruments to obtain complete information on earthquakes.

It is believed such a cooperative program is feasible and that it would develop better mutual understanding in seismological matters among the countries of the Western Hemisphere.

U. S. Coast and Geodetic Survey,
Washington, D. C.

ON TRAVEL-TIME VARIATIONS IN CENTRAL AMERICA

L. M. Murphy

In the process of determining epicenters throughout the world for the past few years definite variations in travel-times have appeared in some regions. One of these regions which has several strong shocks each year is Central America.

Because of the war it is rather difficult to accumulate records or even reports from a large number of stations which will serve as good control-points in locating epicenters. In choosing the Central American epicenters for discussion, there is fairly good control and records are obtainable in nearly all directions from stations having epicentral distances between 3,000 and 6,000 km. Also very many of these stations have high-grade short-period instruments, high magnification, 60-mm time-scales, and good time-control. It is important to bear this in mind since the variations are not of any extreme magnitude. If it were not for the fact that there are exceptionally good stations in the area covered, the subsequent results would have little significance.

In accumulating the data for so many shocks it was thought that there would be an abundance of material available. Although there were many strong and some destructive shocks, it was nevertheless difficult to obtain all of the data desired from many of the stations. Also, only shocks of normal and near-normal depth were considered.

The epicenters were obtained from various sources such as the International Seismological Summary previous to 1935, the Coast and Geodetic Survey Philadelphia Office from 1937 through 1940, and the Washington Office from 1941 to the present time.

The general procedure is to use as the basic data the origin-times, epicenters, and P-readings for the selected shocks. The (P-H)-intervals and the corresponding epicentral distances from the Gutenberg-Richter travel-time tables are obtained for all of the stations. Then using the haversine-method for determining great-circle distances between the stations and epicenters these actual distances are compared with the observed (P-H)-distances. It is nearly always found that the Ottawa distances agree better with the final epicenter than the other east-coast stations. Therefore, in tabulating the data Ottawa has been made the reference-station for comparison with the east-coast stations. After obtaining distance-intervals representing (P-H)-distances minus calculated distances, these differences are compared with the corresponding intervals for Ottawa. The positive values indicate that the arcs are so many km longer than those from Ottawa. Negative values indicate arcs shorter than those from Ottawa.

In Table 1 Fordham and Weston are compared with Ottawa, which is assumed to have no variation. The mean variation for both stations is approximately 39 and 39.5 km, respectively. In obtaining these values, the four epicenters having negative values for both stations are not considered. In these cases it is thought that Ottawa has an unusually late arrival for P. Since the two stations are referred to Ottawa, they would be negative if the usual velocity for P were assumed. Also any value over 100 km is disregarded because of some obvious discrepancy.

In Table 2 an attempt is made to work up the other east-coast stations in the same manner. The agreement is quite good considering the scattered data. With regard to St. Louis, the values represent merely the variations in distances between (P-H) and calculated values. As may be

Table 1--Comparison of epicentral distances and arcs for Weston and Fordham with Ottawa, assuming Ottawa to have no variation

No.	Date	A variation for		Epicenters	
		Weston	Fordham		
		km	km	°	
1	Feb. 22, 1943	+ 20	+ 24	17.9 N	101.1 W
2	June 15, 1943*	- 22	- 12	15.0 N	92.9 W
3	Aug. 31, 1943*	- 56	- 17	14.4 N	91.5 W
4	Mar. 1, 1942	+ 23	+ 26	13.3 N	91.2 W
5	May 14, 1942	+ 13	+ 70	0.3 S	80.0 W
6	July 12, 1942	+ 36	+ 26	0.3 S	80.1 W
7	Aug. 6, 1942	+ 29	+ 44	14.1 N	90.9 W
8	Aug. 16, 1942	+ 17	+ 32	14.0 N	90.0 W
9	Sep. 26, 1942	+ 41	+ 36	12.8 N	87.7 W
10	Nov. 12, 1942	+ 55	+ 43	0.1 S	81.0 W
11	Dec. 26, 1942	+ 46	+ 34	9.6 N	75.6 W
12	Apr. 6, 1941	+ 53	+ 32	13.9 N	88.8 W
13	Apr. 7, 1941*	- 23	- 28	17.6 N	78.3 W
14	July 11, 1941	+ 49	+137[a]	5.3 N	82.7 W
15	Dec. 5, 1941	+ 41	+ 34	8.4 N	83.0 W
16	Dec. 6, 1941*	- 57	- 24	8.5 N	84.4 W
17	May 17, 1940	+ 42	- 24[a]	7.6 N	82.0 W
18	Jan. 20, 1939	+ 21	+ 17	12.9 N	91.8 W
19	Dec. 22, 1939	....	+ 26	9.3 N	84.9 W
20	Dec. 26, 1939	....	+ 78	13.4 N	88.3 W
21	Jan. 2, 1938	+ 19	+ 12	16.2 N	98.5 W
22	Feb. 5, 1938	....	+ 35	5.1 N	75.8 W
23	May 6, 1938	+ 63	+ 3[a]	12.3 N	86.7 W
24	Jan. 28, 1934	+ 47	....	16.9 N	99.6 W
25	July 18, 1934	+167	+ 50	8.2 N	82.6 W
26	July 18, 1934	....	+ 75	8.0 N	83.0 W
27	July 18, 1934	....	+ 73	8.0 N	82.0 W
28	July 21, 1934	+ 47	....	8.2 N	82.6 W
29	Dec. 3, 1934	+ 30	....	14.5 N	88.7 W
30	Feb. 23, 1933	....	+ 17	20.0 S	70.2 W
31	May 8, 1933	....	- 17[a]	17.1 N	100.7 W
32	Oct. 2, 1933	....	+ 12	2.9 S	81.2 W
33	Mar. 14, 1932	....	+ 43	8.2 N	71.9 W
34	May 21, 1932	....	+ 82	13.1 N	87.3 W
35	June 3, 1932	....	+129	19.2 N	104.2 W
36	Oct. 2, 1932	....	+ 36	11.4 N	86.4 W
37	Nov. 2, 1931	....	....	16.4 N	97.0 W
38	July 14, 1930	....	+ 38	14.0 N	89.0 W
	Average[b]	+ 39	+ 39.5	.....	.....

* Four quakes giving unusually slow arrivals for P at Ottawa. [a] Emergent shake. [b] Method for determination explained in text.

seen from the average of -51 km, St. Louis is short giving an early arrival for P. The relations between Pasadena and Tucson are obtained from the differences between (P-H) and calculated values. After determining the second differences in each case a mean of 30 km results. There may possibly be some regional variation near one station or the other. It is difficult to place any definite interpretation on these particular data since both stations may have arcs not passing through the epicenter or only one station intersecting the epicenter.

In considering many of the stronger and more destructive shocks, good correlation of the data for all the stations is observed. Some of these shocks are the following: Near Colima, Mexico, on February 22, 1943; Guatemala City, Guatemala, on August 6, 1942; Manizales, Colombia, on February 5, 1938; and David City, Panama, on July 18, 1934. The Managua (Nicaragua) quake of January 14, 1931, gives very poor data which could not be accepted for any correlation. The quake

Table 2--Comparison of epicentral distances for various stations

No.	Date	Δ for		Δ variation for			
		Pasadena and Tucson	St. Louis	Philadelphia	Columbia	Georgetown	Buffalo
		km	km	km	km	km	km
1	Feb. 22, 1943	+ 3	+ 42	....	....	+ 18	....
2	June 15, 1943*	+ 38	- 35	- 23	....	....	....
3	Aug. 31, 1943*	+ 22	-174	- 9	+ 27	....	....
4	Mar. 1, 1942	+ 42	- 24	....	+ 17	....	....
5	May 14, 1942	+115	- 33	+ 25	+142[a]	+247	....
6	July 12, 1942	+ 85	- 44	+ 70	+ 70	+ 30	....
7	Aug. 6, 1942	+ 45	- 13	+ 7	+ 39	+ 44	....
8	Aug. 16, 1942	+ 23	+ 2	....	+ 13	....	....
9	Sep. 26, 1942	+ 7	- 25	+ 11	+ 7[a]	+ 41	+ 26
10	Nov. 12, 1942	+ 52	....	+ 13	-101	....	....
11	Dec. 26, 1942	+ 35	+ 23	+ 24	+ 32	....	....
12	Apr. 8, 1941	+ 68	- 53	....	....	....	....
13	Apr. 7, 1941*	+ 8	- 35	- 22	- 36	- 14	+ 8
14	July 11, 1941	+ 21	- 40	+ 18	+ 17	+ 65	....
15	Dec. 5, 1941	+ 35	....	+ 24	+ 25	+ 41	+ 57
16	Dec. 6, 1941*	+ 30	+ 44	- 54	+ 26[a]	- 10	- 10
17	May 17, 1940	+ 45	+ 6	+ 42	+ 27	....	....
18	Jan. 20, 1939	+ 24	....	+ 23	+ 13	....	....
19	Dec. 22, 1939	+ 17	- 68	+122	+106	....	....
20	Dec. 26, 1939	....	- 40[a]	....	....	....	....
21	Jan. 2, 1938	+ 22	- 10	+ 31	+ 35	....	....
22	Feb. 5, 1938	+ 46	....	+ 60	....	....	....
23	May 6, 1938	+ 2	....	....	....	....	....
24	Jan. 28, 1934	0	- 78	....	....	+ 9	+ 11
25	July 18, 1934	+ 13	- 44	+ 16	+ 55	+ 39	....
26	July 18, 1934	+ 59	- 68	....	....	....	....
27	July 18, 1934	+ 23	- 45	....	....	....	....
28	July 21, 1934	....	- 44	- 43	+ 13	+ 55	....
29	Dec. 3, 1934	+ 21	-138	- 51	....	+ 43	....
30	Feb. 23, 1933	+ 40	-125	....	+ 54	+ 16	....
31	May 8, 1933	+ 52	-100	....	+ 17	+ 37	....
32	Oct. 2, 1933	....	- 89	....	....	....	....
33	Mar. 14, 1932	+ 12	- 44	....	+ 65	+ 31	....
34	May 21, 1932	....	-177	....	+ 69	+ 25	....
35	June 3, 1932	+ 23	- 63	....	+146	+ 47	-110
36	Oct. 2, 1932	+ 14	- 80	....	+ 45	+ 56	+ 23
37	Nov. 2, 1931	+ 34	....	....	....	+102	....
38	July 14. 1930	....	- 96	....	....	+ 25	....
	Average[b]	+ 30	- 51	+ 28	+ 34	+ 38	+ 29

* Four quakes giving unusually slow arrival for P at Ottawa. [a]Emergent shake. [b]Method for determination explained in text.

of September 26, 1942, although not severe, is a very good example for the travel-times of all the stations under consideration.

In conclusion, it may therefore be said that the east-coast stations have a slower travel-time for the longitudinal wave, that St. Louis has an early arrival time. and that either Pasadena or Tucson has a small apparent local variation.

U. S. Coast and Geodetic Survey,
Washington, D. C.

EARTHQUAKES OF SOUTHERN MEXICO AND CENTRAL AMERICA WITH SPECIAL REFERENCE TO PROFESSOR WM. H. HOBBS' THEORY ON "NEW VOLCANOES AND A NEW MOUNTAIN RANGE"

O. W. Swainson

Professor WILLIAM H. HOBBS of the University of Michigan, well known to us as the author of Earthquakes, an introduction to seismic geology, has proposed the theory that a new mountain range and volcano-chain are developing along the Pacific Coast in southern Mexico and Central

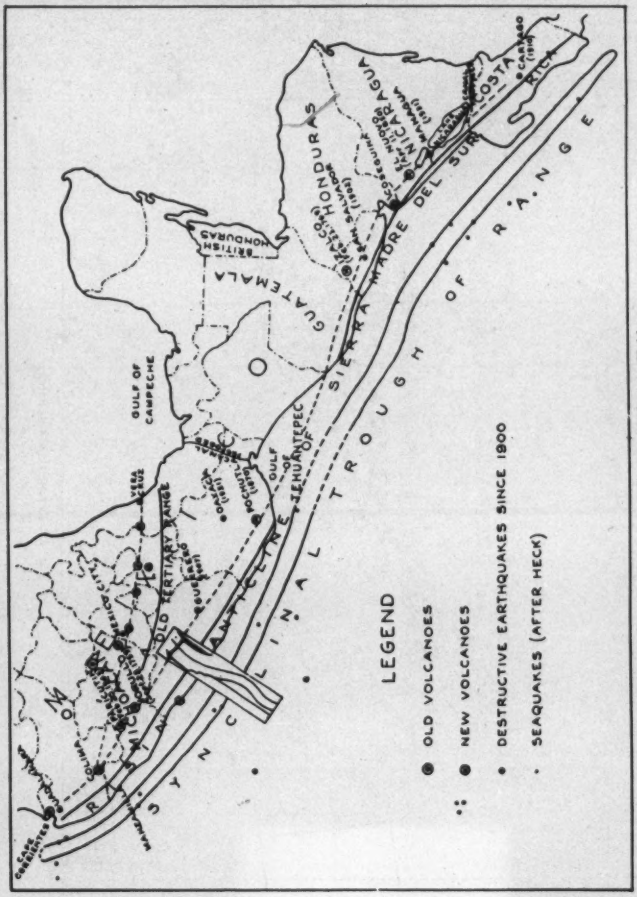

Fig. 1--Rising anticline according to Hobbs

America [see 1 of "References" at end of paper]. He bases his contention on the new volcanoes that have been born from flat land, on unusual seismic activity, on rising coastal ridge evidenced by wave-cut terraces, and on offshore phenomena such as a deep trough near and paralleling the coast-line and seismic sea-waves.

In Figure 1 (taken from HOBBS' article) note the east-west "volcanic axis" about latitude 19°, the chain of new volcanoes extending along the Pacific Coast including the still active and growing Parícutin, the offshore deep trough, and the supposedly new mountain range. The trough and mountain ranges are shown as broken at the Gulf of Tehauntepec.

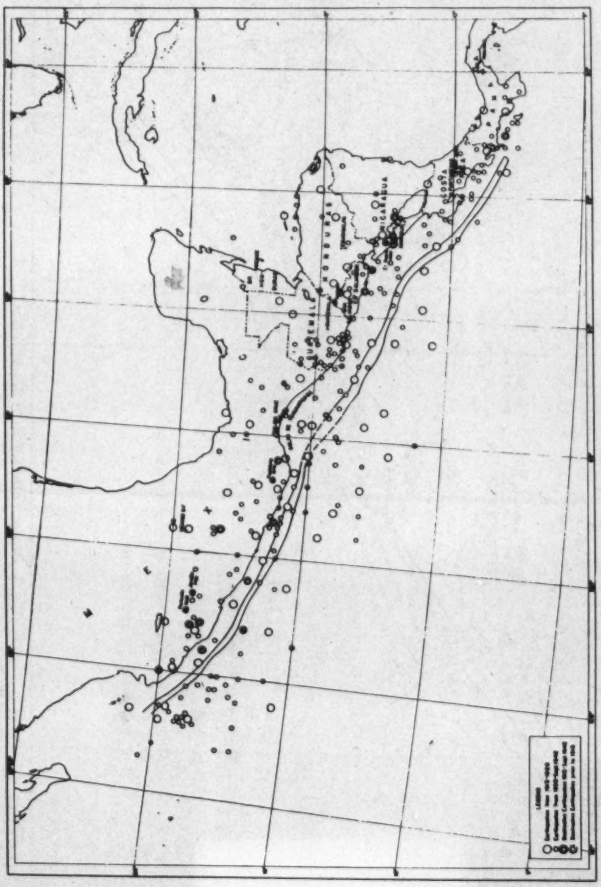

Fig. 2--Earthquake epicenters

HOBBS has made some interesting and stimulating suggestions in his article. It is not my place to pass on the validity of his geological conclusions, but I would like to give a little additional information on the earthquake-history which he did not have, especially the positions of instrumentally located epicenters. Although the locations of many of these are not perfect owing to scarcity of seismograph-stations, they are quite good.

In Figure 2 I have shown about 250 epicenters in the region under discussion, those from 1913 to 1930 being taken from Miss BELLAMY'S Index catalogue of epicenters and for the remaining

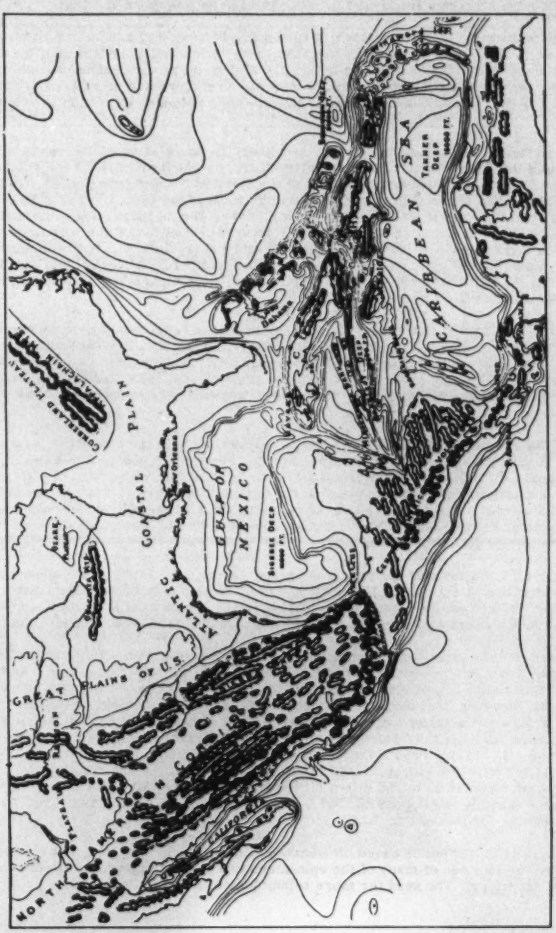

Fig. 3--Generalized map showing topographic and geological structures and trends (after Schuchert)

period through September, 1942, from United States Coast and Geodetic Survey annual lists. The former are shown by large circles and the latter by small ones. The positions of those which B. GUTENBERG later designated as deep focus are plotted in accordance with his interpretation. The number of circles given is by no means the total number of shocks as many were repeated in practically the same place, including some strong aftershocks. The more destructive shocks are indicated by double circles. An attempt was made to locate a few of the more important earthquakes that occurred in Central America before 1913 back to 1528, but available information usually gives only a general idea of the area affected and not enough to ascribe an epicenter. A few are shown by large dashed double circles. The annual earthquake activity was quite variable.

One striking feature is the great number of epicenters between 11° and 20° north farther offshore than the submarine trough, indicating that there may be instability of the crust in this region. The positions of the sides of the deep trough paralleling the coast is somewhat uncertain, but taking into account this and the uncertainties of epicenters, there are some 37 shocks in or near the trough. As they are scattered along its extent, there seems to be reason to relate them to it.

The chief interest of the seismologist in this region is in the relation of the trends of structure roughly paralleling the Pacific Coast and the east-west trends which are seen in the volcanic axis and farther south extending toward the south side of the Bartlett Trough (see Fig. 3). GUTENBERG [2] points out that the Caribbean Loop is not as active as most of the circum-Pacific Belt. It may be that the activity of the Pacific Belt in this Pacific Coast Region is increasing while that of the loop is decreasing. This is a matter of considerable interest. Conditions which produce a loop are of importance and can best be studied in Colombia and Venezuela and in the region discussed. I will not offer an opinion but refer you to such authorities as HILL, VAUGHAN, and SCHUCHERT. I might say that ALEXANDER AGASSIZ stated that the Caribbean structurely and biologically is more like the Pacific than the Atlantic.

As to seismic sea-waves, HOBBS has perhaps appraised the regional activity a little too highly. He lists the activity as third in the Pacific after Japan-to-Kamchatka and the Dutch East Indies. South America is far more active than the Mexico-Central America Region. Of 13 seismic sea-waves in the last-named region, six occurred in the years 1928 and 1932, and only two, both in 1859, are listed for Central America. The seismic sea-wave activity is substantial, but not outstanding.

The United States Coast and Geodetic Survey in cooperation with the respective countries of Costa Rica and Mexico maintains automatic tide-gages at Puntarenas (Costa Rica) and Salina Cruz (Mexico). These are strategically located to indicate any differential changes in elevation of the coast-line. If the mountain range were broken at the Gulf of Tehuantepec, this section being stable, as HOBBS claims, the tidal bench-marks at Salina Cruz would indicate no change in sea-level, while the one at Puntarenas would if a change occurred there. The gages have not been in operation long enough to give this information.

The other question, of whether the trough is broken opposite the Isthmus of Tehuantepec, thus giving another indication of stability in the section, can be settled only by additional surveys. There are a few soundings which might indicate that the deep trough may be continuous, but for HOBBS' purpose only a complete survey of the indicated doubtful area would suffice.

HOBBS states that the more stable conditions and lesser earthquake-activity at the Gulf of Tehuantepec make that a better location for a second canal than the Nicaraguan site. As to the latter the broad conclusion is that if there is a growing mountain range, earthquake-danger exists. Figure 3 indicates, however, that most of the earthquake-activity of Nicaragua has been in the general region of Managua and has consisted chiefly of intense but rather local shocks. The activity in the southern part of Lake Nicaragua, which would be traversed by the proposed canal, has been rather small. Major-General DAN I. SULTAN, United States Engineers, who visited Managua immediately after the earthquake of 1931, states [3] that: (1) The region traversed by the proposed Nicaraguan canal is 60 to 200 miles distant from the active Managua Region; (2) earthquakes of the same intensity as the one of 1931 would not damage the canal-structures unless they occurred very near to either locks or dam.

The discussion in this paper is based on somewhat inadequate geophysical data. From the seismic viewpoint the location of many of the epicenters are insufficiently accurate to relate them to the geological structure. The need for more seismological stations is obvious.

Professor HOBBS' paper emphasizes the dependence of geological interpretation on geophysical observations.

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[2] GUTENBERG and RICHTER, Seismicity of the Earth, Sp. Paper No. 34, Bull. Geol. Soc. America.
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CHARACTERISTICS OF ALASKAN EARTHQUAKE-RECORDS AT DISTANCES OF 40° TO 70°

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(Abstract)

The records of Alaskan earthquakes are often confused and difficult to interpret. Many shocks are complex and others are deeper than normal but not deep enough to show distinctly the phases peculiar to deep-focus quakes. Locations of epicenters are usually only reasonably good. Alaska and the Aleutians have been mapped seismically by SIEBERG and the whole region has been discussed by GUTENBERG and by HECK.

For the purposes of the present study, five regions have been considered, namely, the Aleutians, the Alaskan Peninsula, Kenai Peninsula, Kodiak Island, and East Alaska. Only records written at Fordham were studied; the distances vary from 40° to 70°; epicenters were taken from the reports of the United States Coast and Geodetic Survey and the Jesuit Seismological Association.

GUTENBERG has listed the characteristics of earthquake-records at these distances; ADKINS has studied the earthquake of July 27, 1937, with epicenter at 64°.6 north and 146°.5 west; MUKHERJEE and RANGASWAMI have studied the very intense shock of November 10, 1938, at 55°.3 north and 158°.5 west. We have examined the Fordham records with the results of these investigators in mind, hoping to detect definite trends which may lead to conclusions about structure, paths, and travel-times.

From 1928 to 1944, 104 Alaskan shocks have been recorded sufficiently well at Fordham to be included in this investigation. Table 1 shows the phases that have been clearly identified on the records of the different regions; the trends are indicated by L for late and E for early. The phenomena worthy of note are the late P and early S, the scarcity of reflected phases, and the lateness of the surface-waves.

Table 1--Phases for Alaskan earthquakes

Region	No.	Phase														
		P	PcP	pP	PcS	PR_1	PR_2	S	sP	ScS	sS	sSS	PS	SR_1	SR_2	L	M
Aleutians	38	36	8	5		1	3	30		7			10	6	4	21	25
Alaskan Peninsula	35	25	3	2		3	1	24	1	7			7	6	5	17	19
Kenai Peninsula	14	11	2	1	2	3	1	11		1	1	1	1	4	1	8	10
Kodiak Islands	4	4						3		2			2	1		2	2
East Alaska	13	9	2	1		6	1	9		2	1		2	7	2	7	11
Total	104	95	15	9	2	13	6	77	1	19	2	1	22	24	12	55	67
Trend	...	L	..	..	..	L	L	E	..	..	..	..	E	L	L	L	L

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EARTHQUAKES ON THE EXPANDING EARTH

Anatol James Shneiderov

(Summary)

Introduction--The inadequacy of physical science limits the attainment of ultimate truth because of (1) probable error of observation preventing accuracy of experimental verification and (2) the transition of quantity into quality on the basis of dialectical materialism.

The author's object is to present the result of his research for the past few years in the line of seismic prognosis on the basis of geodetic, astronomical, and seismo-statistical observations, and to develop the ideas given in his preliminary exposition in the Transactions of 1943.

The causes of earthquakes are derived on the basis of the Earth's expansion due to deformation and expansion of its atoms under the inverse cube differential gravitational forces. Variations in solar activity and in pulsation are due to causes similar to those which produce pulsation and expansion in the Earth. The following sections summarize briefly the author's discussions.

The expanding Earth as a physical reality

The parallelism of oppositely situated coasts, the swelling of ocean beds, and the rebound-theory of earthquakes suggest a radial expansion of the Earth. This can be explained as a transition of the deformed and expanding atoms of the Earth from a lower level of energy to a higher one, thus providing a foundation for establishing the Earth's expansion as a phenomenon existing in reality.

The constitution of the Earth

The Earth is considered by the author as composed of a central gaseous core of high density, and of strata of liquid, plastic, semi-plastic, and elastic magma covered with its crust. Due to different chemical composition and physical states in the layers, the degree of ionization in them differs, giving rise to electrical stratification of the interior of the Earth, as well as of its gaseous envelope.

Atoms, their nuclei and shells

The "smeared" electron of the wave-mechanical physics is represented by an electron performing trillions of revolutions per second around its atomic nucleus. The "planetary" orbit of this "shellar" electron varies with time in its radius-vector as well as in its orientation in nucleo-centric coordinates. The variation in the distribution of an occurrence of definite types and sizes of orbits in time and space corresponds to the probability-function in wave-mechanics. A system of a nucleus and of "electron shells" superimposing and impregnating one another is pictured as an atom.

An atom between two planets

The effects of electrostatic and gravitational forces--While the electrostatic force between a nucleus of an iron atom and one of its shellar electrons is of the order of 1.5×10^{-2} dyne, the gravitational force between the same nucleus and electron is of the order of 1.5×10^{-41} dyne. Furthermore, the gravitational force with which Jupiter attracts the mass of one of the Earth's electrons is 10^{9} times greater than that with which the iron nucleus attracts the mass of its shellar electron. Due to the great distance of the planets from the Earth the gradient of a planetary gravitational field imposed upon an atom of the Earth is considered as negligible.

Electrostatic and gravitational accelerations--The acceleration of 10^{-5} cm/sec^2 produced by Jupiter on any one of the Earth's electrons is considered significant when compared to the apparently negligible gravitational force and to the size of an atom (2×10^{-8} cm).

The geometrical consideration of perturbations produced in an electron-shell by a planet--The perturbing acceleration of a shellar electron due to the parallactic inequality of its orbit with respect to the center of the perturbing planet is of the order of 10^{-47} cm/sec^2 (in the case of Jupiter) and can be disregarded because of its smallness. Thus

$$(F_m - F_{m'}) = -(GM/R^2)\,[(2a_o/R - a_o^2/R^2)/(1 - a_o/R)^2 - (2a_o/R + a_o^2/R^2)/(1 - a_o/R)^2] \approx -(4.2 \times 10^{-5})\,(1.95 \times 10^{-43})\,(1 + 1.3 \times 10^{-43}) \text{ in cm/sec}^2$$

Here F_m and $F_{m'}$ are the maximum and minimum accelerations, respectively, produced by the mass M_2 on an electron on the opposite sides of its orbit of radius a_o, R is the distance of the atomic nucleus from Jupiter, and G is the gravitational constant.

The magnitude of the tidal perturbation produced in an electron-shell by a planet is inversely proportional to the cube of the distance between the planet and the electron-shell, the tidal acceler-

ation being of the order of 10^{-26} cm/sec^2. Although considerably greater than the parallactic-inequality perturbation, the tidal perturbation, being independent of time, cannot increase with time, and therefore can not make the Earth expand above an insignificant value. Thus in cm/sec^2

$$A_{ex_2 max} = (4GM_2 a_0/R^3) \approx 2.1 \times 10^{-26} \text{ in cm/sec}^2$$

where $A_{ex_2 max}$ is a differential acceleration of an electron by Jupiter, which produces a tidal effect in the electron-shell.

Emphasis is placed on the difference between the microcosm and the macrocosm time-scales, a "year" of the former being 10^{22} times shorter than that of the macrocosm.

The perturbations in electron-shells of an atom placed between two planets--The differential effect of two oppositely directed variational perturbations produced by two planets in an atom placed between them is dependent on time, thus making a shellar electron describe an expanding spiral orbit when its atom's nucleus is in syzygies with two planets.

On a classical mechanical solution of a problem of a perturbed electron-shell--In a limited four-body problem, a general solution for an orbit described by a shellar electron under a syzygial perturbing-force inversely proportional to the cube of the distance is one or another of the family of Cotes' spirals, depending upon initial conditions.

The differential equation for this case is

$$f = [R^2 (d\vartheta/dt)]^2 (1/R^2)\left\{[d^2 (1/R)/d\vartheta^2] + (1/R)\right\}$$

where f is an inverse-cube central perturbing-force, t is time, and R and ϑ are polar coordinates.

The time-factor--Being dependent upon time, the syzygial perturbation of shellar electrons produces an effect which is cumulative in character, and which makes shellar electrons spiral out during a syzygies and spiral in when not in syzygies. Hence, expansion and contraction of the Earth's atomic structures continue in some cases for tens and hundreds of years, and recur periodically. This, in turn, makes the Earth pulsate with periods of from several hours to more than 200 years. The relative amplitudes of pulsation are directly proportional to the second power of the duration of a syzygial action, and inversely proportional to the third power of the distance if the second and the further members of the series are disregarded.

The departure of a shellar electron under an inverse-cube perturbing-force from its atomic nucleus, for an isolated atom, is

$$S = 2GMa_0 (t^2/R^3) + (1/2) (GMa_0)^2 (t^4/R^7) + \ldots \text{ in cm}$$

Syzygial families--The celestial syzygies which affect the Earth are divided into nine families, and the latter into leaders and expanders.

The possibility of a wave-mechanical solution of the problem--BORN'S perturbation-method in the treatment of a syzygial perturbation by SCHRÖDINGER'S wave-equation is suggested.

The wave-equation has been used in the form

$$\Delta\Psi - (8\pi^2/h^2) (V + (\lambda \cdot 4GMa_0/R^3) \cos\phi) \Psi + (4\pi i/h) (\partial\Psi/\partial t) = 0$$

in which

$$\Psi = \psi \exp(-2\pi iEt/h)$$

Therefore $(\partial\Psi/\partial t) = -(2\pi iE\Psi/h)$

In a treatment of several limited cases of syzygial perturbation it has been found that the product of ψ with its conjugate ψ^*, which in this case is equal to ψ^2 (because ψ is real), is a function of time t, so that

$$\psi^2 \sim dx/m(dx/dt) \sim dt$$

In the above formulas E is the total energy of the electron, V is its potential energy, h is PLANCK'S constant, ψ is the amplitude of the waves of matter, and λ is a constant of the dimension ML. This

result shows that the probability of finding the perturbed shellar electron at a distance farther from the nucleus grows greater with a longer period of syzygies or, in other words, that the atom expands while being under syzygial conditions.

The red shift in the spectra of the Sun and the stars can be explained as a result of tidal and syzygial deformations of radiating atoms.

The liberation of shellar electrons

The force of gravity opposing the expansion of atoms--The action of the imponderable matter within the Earth prevents the Earth from bursting, and a squeezing of the Earth's atoms into one another takes place during expansions.

The intra-atomic collisions of shellar electrions--Due to the intersecting of one electron-shell with others of the same atom there exists a rigid relation between (a) the forms of the orbits and their relative sizes, and (b) the velocities and their distribution, which determines an absolute stability of an atom, when its electrons are considered mathematical points. With the finite dimensions of electrons, and the elastic properties of their spheres of electrostatic action, no atom can be considered as absolutely stable, the "life" of an atom being a function of the factors (a) and (b) given above and several other factors. This makes the solution of the stability-problem for poly-electronic atoms extremely tangled and practically indeterminable by the theory of groups.

Every slight perturbation in the equilibrium of an electronic configuration within an atom increases the probability of a collision of its electrons. Consequently, some quantity of electrons is liberated because of collisions due to tidal and syzygial perturbation of shellar electrons.

The extra-atomic collisions between shellar electrons--Because the molecules and atoms inside the Earth are compressed together by force of gravity, they tend to penetrate one another while they are expanding, thus causing the electrons on the outer shells to collide with those of other atoms. This produces considerable ionization of atoms and a quantity of free electrons in the region under expansion due to syzygies.

The transmission of expansion-pressure from atom to atom--Because of the form of the gravity-curve and of the pressure inside the Earth, the penetration of one atom into another under syzygial perturbation, as well as the density of electronic gas made of liberated electrons, is greatest at the Earth's center.

The dynamical model of an atomic shell--The author's concept of an atom is a system composed of shellar electrons interimposing and impregnating one another's shells around a common nucleus. The probability of presence can be interpreted on the basis of the dynamical model presented.

The interaction between strong and weak atoms--The stronger atoms, represented by smaller shells and greater velocity of nucleocentric revolution of shellar electrons, break into the weaker atoms, exciting and ionizing them. The excited atoms are weaker than normal ones, and therefore lose their electrons more easily. The recombination-process is slower than the ionization-process.

The location of the expanding processes in the Earth

One more family of syzygies--The tenth family of syzygies is the Earth's gravity-family of syzygies. When this syzygies acts on an atom inside the Earth the differential tidal force is formed by the mass of the Earth itself from one side and by a celestial body from the other, the Earth's gravity taking the part of a leader in the gravity syzygies with respect to the Earth's constituent atoms, except in the central region, where the celestial body takes the syzygial leadership. The expansion of the Earth under this syzygies is unsymmetrical.

The Earth's gravity-syzygial expansion--The gravity-syzygies makes one-half of the Earth expand when the opposite half contracts. This syzygial action deforms the Earth's spheroid into an ovoid or geoid. The maximum strain in the Earth's crust is on the "thin end" of the ovoid.

Terrestrial magnetism may arise from the fact of a continuous migration of free electrons from the regions with a denser electron-gas at the thick end of the ovoid to the region of thinner electron-gas at the thin end of the ovoid. This migrational electronic motion has a circular component, due to the diurnal rotation of the Earth.

The inflation of the Earth and the effects of the inflation

The molecular and electronic gases in the Earth--Under the "squeeze" of gravity and pulsational expansion, atoms within the Earth ionize, losing their shellar electrons. The latter, having a specific gravity of the order of 10^{11} gm/cm^3 and being turned into free electrons, impregnate the structure of the Earth as an electron-gas. A continuous action of gravity on free electrons makes them "sink" to the center of the Earth, forming an electronic concentrate around the "hearth" of the planet. Such a concentration of electrons at the center of the Earth makes necessary an electrical stratification of the interior, with concentric layers of high positive charge somewhere between the center and the "hearth". Thus the Earth becomes a spherical condenser. In general, the Globe may be thought of (1) as a suspension of highly ionized atoms in an electronic and neutronic concentrate within the boundary of the central core of about 0.54 of the Earth's radius, (2) as a solution of electron-gas in atomic gas nearer the core, and (3) as a solution of free electron-gas in molecular gas and in semi-plastic, plastic, and elastic Earth's strata.

The Earth's internal equilibrium--The Earth's internal equilibrium is represented by (1) the gravitational compression versus centrifugal force of shellar electrons and (2) by the internal gaseous pressure versus the strength and elasticity of the Earth's crust and sub-crustal layers. The transmutation of elements is considered possible because of a probability of a shellar electron's falling on the nucleus.

The conditions in the Earth's crust--The pressure of the gaseous core produces a continuous pressure on the crust and sub-layers from inside. This makes the Earth stretch its "skin" to a limit close to the combined tensile strength of the crust and the sub-layers. Besides, a continuous battering of the liquid layer on the boundary of the Earth's gaseous core by free electrons and highly agitated atoms makes the liquid boundary-layer evaporate and ionize, contributing additional free electrons to the core. This process has made the core inflate and expand the Earth extremely slowly, but continuously, through billions of years. Stretched almost to the limit of its elastic strength by this continuous inflation of the core, the Earth's crust ruptures and faults at each syzygial pulsation, producing earthquakes.

The causes of earthquakes

The classification of the causes--The causes of earthquakes are classified into three groups as (1) primary, (2) secondary, and (3) tertiary, in order of their importance in inducing seismic activity in the Earth.

The primary causes--To the primary causes belong (1) continuous inflation, (2) pulsation, and (3) syzygial deformation of the Earth.

The pulsations of the Earth are subdivided into those which are due to the Earth's gravity-family of syzygies and those due to planetary influence. The latter group consists of two subgroups--(a) the slow syzygial pulsations caused by the major planets and (b) the rapid syzygial pulsations caused by the Moon, the Sun, and the minor planets.

The secondary causes--The tidal deformation of the Earth and the deformations due to the centrifugal force of the Earth's diurnal rotation are the secondary quake-producing causes. The tendency of the latter cause to produce earthquakes is concentrated within the belts between 27° and 45° and 18° and 37° in the Northern and Southern hemispheres, respectively.

The Tertiary causes--To tertiary causes are referred (a) the non-uniformity in the strength of the Earth's crust and subcrustal layers, (b) the unstable equilibrium in the crust produced by previous differential displacements in the crust, (c) the variation in terrestrial electromagnetism induced by cosmical sources, and (d) all other causes.

The planetary configuration--In the effect of the planets, the Moon, and the Sun upon the Earth the amplitude and the period (or rate) of syzygial pulsation is equally important. The maximum seismicity manifests itself when the combined effects of the amplitude and the rate of pulsation are at maximum. An investigation of 15 major earthquakes shows that they all occurred during the "bunching" of celestial bodies in celestial longitude, which "bunching" corresponds to the above-mentioned maximum in the combined effects of the amplitude and the rate of expansion.

The time of the position of the Moon at perigee or apogee, as well as at high altitudes, is favorable for an earthquake-occurrence. Fourteen earthquakes out of the 15 investigated occurred

with Mercury at low altitudes.

The tectonophysical and morphological changes resulting from the continuous expansion and syzygial pulsation of the Earth

A model of the Earth--A model of the Earth constructed in a mental experiment helps in visualizing the changes incurred by the expansion and pulsation of the Earth.

The continuous expansion and the pulsation--The operation of the model of the Earth by electric heating and cooling produces an effect analogous to syzygial pulsation.

The origin of plutonic earthquakes--Plutonic earthquakes occur because the deeper and more plastic subcrustal layers of the Earth contract more quickly than the layers closer to the crust. This causes laminar ruptures in the subcrustal layers, observed as plutonic earthquakes.

The tectonic earthquakes and the formation of seas and continents--A corrugation of the non-plastic crust of the Earth takes place when it contracts after an expansion. The pulsations, repeated for billions of years, produce a deformation of the crust, enhancing the extensive corrugation. The crests of the corrugated areas are the continents and the troughs are the seas and oceans Tectonic earthquakes tend to occur during the half-periods of expansion, because of the stresses in the stretched crust and the sub-crustal layer.

The conduction of heat out from the interior of the Earth and the result of this process--With the Earth's core growing in radius, the magmatic layer, which insulates the core from the outer space, becomes thinner, while the surface area of the Earth becomes larger. This process leads firstly to a greater radiation of the central heat through the surface of the Earth, and secondly to the prevalence of the Earth's pulsations due to the core-pulsations, rather than to those of the intermediate layers.

With the growing core and the decreasing thickness of liquid and solid magmatic layers between the crust and the core, a moment may come when the internal gaseous pressure in the core explodes the Earth into fragments, which in time may spread into another belt of asteroids around the Sun.

The prognostic possibilities in seismology

The three components of the prognosis--The three components are represented by (1) the geodetic method, (2) the astronomical method, and (3) the seismo-statistical method.

The geodetic component in the seismic prognosis--The use of the radio interferometer for a direct measuring of the expansion in the Earth's crust is a good method of determining the yielding-point of the expanding crust which is usually followed by a rupture or fault. This component is useful in determining local strains and impending earthquakes, forecast on a short scale of time.

The astronomical component in the seismic prognosis--Earthquakes can be predicted on a greater scale of time by means of celestial mechanics. The resultant of syzygial expansions, their amplitude, rapidity, and time can be determined with great accuracy for many thousand years ahead, and for any particular moment of time.

The determination of celestial configurations can be made either analytically or by a mechanical integrator, suggested as a geoplanetarium later in this paper. The possibility of the recurrence of cataclysmic earthquakes, any one of which might totally destroy human civilization, within a period of from 30,000 to 150,000 years is a useful hint for the human race to think over.

The statistical component in seismic prognosis--An increased number of seismic stations, covering the whole Earth, must accumulate data for the computation of the total energy dissipated per given unit of time in earthquakes over the whole Earth by the sectors into which the surface of the Earth is sub-divided. Upon calculating the average liberation of seismic energy by a particular area, its lagging or advancing from the calculated average serves as a good statistical criterion in seismic prognosis.

The scientific prognosis of seismic disturbances

A picture of a future earthquake presents a good opportunity for a demonstration of the practical composition of the three components for the determination of the date, the place, and the intensity of an earthquake disturbance.

Sufficient warning allows practical steps to be taken in the preservation of life and property.

The astronomical component proves the most useful in furthering preparedness in case of impending earthquakes.

The geoplanetarium

A recording of inverse-square forces--A model of the solar system built on the scale of $1{:}1.495 \times 10^{11}$, except for the sizes of the planets, the Moon, and the Sun, and equipped with electronic devices, is capable of recording variations in the gravitational acceleration of the Earth by the rest of the celestial bodies.

The recording of inverse-cube forces--An application of CHILD'S law to the device explained in above paragraph makes it possible to record variations in tidal and expansion forces and accelerations.

The recording of acceleration inversely proportion to the third power of the distance--It is possible also by means of the geoplanetarium to record and integrate electromechanically, variations in the expansion with time, inasmuch as this variation is inversely proportional to the third power of the distance.

The solar variation due to celestial configurations

The solar variation--The nature of syzygial expansion is the same for the Sun as it is for the Earth. Therefore, the Sun is subject to syzygial pulsations and continuous inflation which manifest themselves as prominences and solar spots analogous to seismic disturbances. The periodicity in solar activity is, however, less complex, because of the absence of orbital motion and the central location of our luminary with respect to the planets.

The stellar variation--The variation in the class of pulsating stars is also due to syzygial perturbations. Each of such stars must have several (at least two) satellites or planets to form syzygies.

The origin of planetary systems--According to the author's concept, every planet--whether of solar or stellar origin--is formed from the spheroidal film of a star's gaseous layer. When accompanied by a sudden increase in internal pressure and by considerable axial rotation, a strong syzygial pulsation is capable of throwing away radially a star's surface layer. This spreads into a thin gaseous envelope, a spheroidal film, which later breaks and condenses into a planet.

The nova and supernova--When the thin gaseous envelope is thrown from a star, a nova appears in the sky, and when the whole layer of matter above the central electronic core is blown away, a supernova brightens the sky, provided the distance and location make the star observable from the Earth. The electronic core which remains after the flash of a supernova is a white dwarf.

Syzygial expansion in the atmosphere of the Earth as a cause of the atmospheric-electrical stratification

Syzygial pulsations in the Earth's atmosphere produce different degrees of ionization at different altitudes. The syzygial pulsation-theory gives the explanation for the variation in altitude of the Heaviside layer and of other ionized layers.

Conclusion

The spiral orbit should be considered as the most usual case for any real planetary or electronic revolutional motion under central force. All orbits which we determine as elliptical are in reality spirals.

J. K. E. HOLM in "An astronomical aspect of the evolution of the Earth" [J. Astron. Soc. South Africa, vol. 4, No.1, 1935] also asserts that the Earth expands as a whole. He gives the formula $(T_{eff}/\delta^{0.38}) = 145$, where T_{eff} = surface-temperature in °K and δ = mean density, and presents some proofs that there is real expansion.

The cases of the differential movements present in the crust of the Earth, the variations in latitude and longitude, and the vertical displacements brought to light in Dr. STETSON'S paper are in conformity with the ideas developed in this paper.

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AN EXTENSION OF THE METHOD OF NUMERICAL INTEGRATION OF SEISMOGRAMS TO INCLUDE A THIRD INTEGRATION

Edward J. Walter

(Abstract)

This investigation is concerned with the problem of integration of a galvanometrically recorded seismogram in order to obtain a record of actual ground-motion. The integration-process must be carried out over three integrations or summations and hence it has been necessary to extend the theory of the double integration-process as developed by Neumann and others in the United States Coast and Geodetic Survey to include a third integration. The essential problem therefore is one of determining the nature of the cumulative error and a method of correcting this error. The method is then applied to a seismogram produced by a known motion. The following results were arrived at:

(1) The error-curve involved in triple integration is a cubical parabola. The nature of this curve is shown in Figure 1.
(2) The error is not constant or linear, but is a function of each particular ordinate and is probably due to our inability to make consistent, precise measurements. Superimposed on this random error may be other constant or linear errors more easily detected.

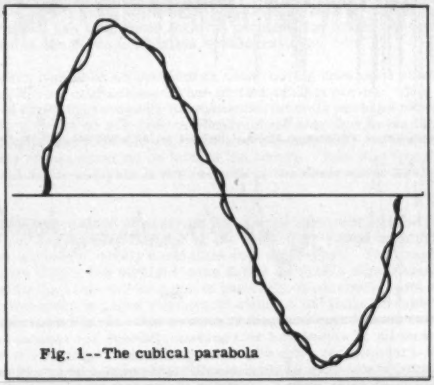

Fig. 1--The cubical parabola

(3) No one correction-factor will be sufficient; hence factors should be determined for small intervals. Constants of integration must then be determined for these small intervals.
(4) The method of applying these correction-factors and constants of integration limits cumulative error to the small intervals selected and removes the necessity of using highly precise factors.
(5) The beginning motion is masked by transient effects due to both the seismometer and the galvanometer. The results are limited to the range beyond which the transient are effective unless they are eliminated. With these restrictions the method seems to give fairly good results for the limited range over which it has been applied.

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PERIOD-AMPLITUDE ANALYSES OF STRONG-MOTION RECORDS

Frank Neumann

The engineer interested in designing structures to withstand earthquakes wants to know first of all the nature and magnitude of the ground-motions to which the structures may be subjected. These motions can be expressed in the form of complex curves showing continuous records of acceleration, velocity, and displacement or, in a more comprehendable way, especially for analytical purposes, by selecting groups of outstanding or maximum amplitude-waves and associating them with the corresponding periods assuming that the motions are of simple harmonic character. Just how good a substitute such period-amplitude data are for the actual ground-motion we do not know. The point of the problem is that the use of actual ground-motion in almost any type of engineering re-

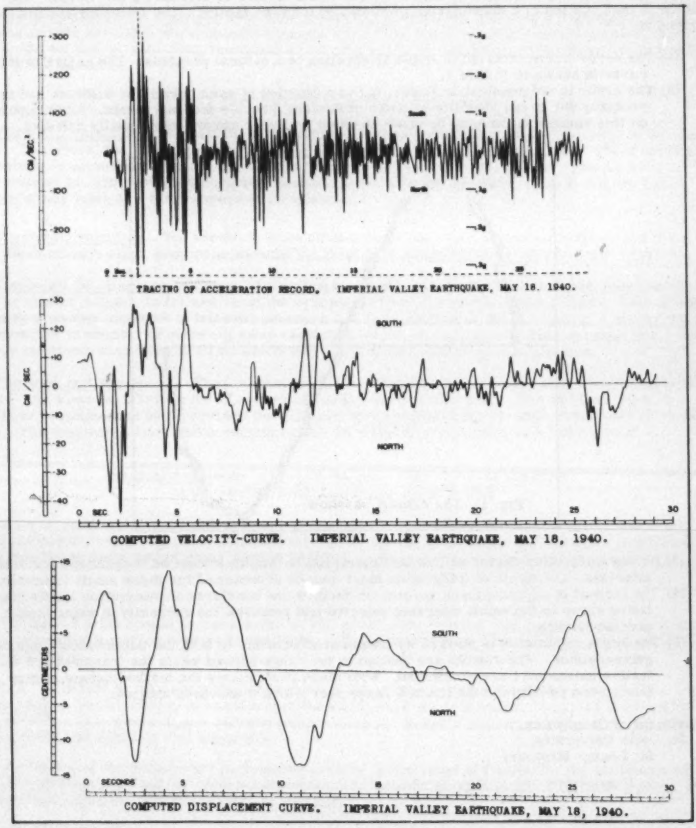
TRACING OF ACCELERATION RECORD. IMPERIAL VALLEY EARTHQUAKE, MAY 18, 1940.
CM/SEC
SOUTH
NORTH
COMPUTED VELOCITY-CURVE. IMPERIAL VALLEY EARTHQUAKE, MAY 18, 1940.
CENTIMETERS
SECONDS
COMPUTED DISPLACEMENT CURVE. IMPERIAL VALLEY EARTHQUAKE, MAY 18, 1940.

Fig. 1--Acceleration-, velocity-, and displacement-curves, all representing the same ground-motion

search involves so much labor in the integration-processes that are demanded that it seems worth while to thoroughly investigate any simpler procedure that might achieve the same result.

The standard accelerograph of the United States Coast and Geodetic Survey is supplemented by a few instruments of other types but we must look to acceleration as the basic element of motion with which we have to deal. Because of the relatively high frequency of the vibrating pendulum of the accelerometer and the fact that the highest accelerations are invariably associated with the short ground-periods, a strong-motion acceleration record yields satisfactory data only for short-period waves. These are always associated with small, almost minute, displacements. The longer ground-periods are revealed only by integrating the acceleration-curve one time, thus producing a velocity-curve, and integrating this velocity-curve to obtain the corresponding displacement. Figure 1 serves to show how the longer-period ground-waves are accentuated with each integration. We assume that the periods apparent on the various curves are actual ground-periods--an assumption which is theoretically true in the case of sustained harmonic motion of the ground, but not always true in practice as strong-motion records are sometimes extremely complex.

While it is obvious that a series of periods and amplitudes may be read from either an acceleration velocity- or displacement-curve, it is also practicable to compute from any one curve the corresponding values in the remaining two elements of motion using the well-known relations a (acceleration) = [$4\pi^2$ A (amplitude)/T^2 (ground-period)] and V (velocity) = aT. In the case of integrated accelerograph-records a single reading not only produces period-amplitude data in the two remaining elements of motion but rather frequently furnishes a check on the estimated period which is sometimes of questionable accuracy. The check results from the fact that no amplitude computed by the formulas can be greater than the acceleration originally recorded, or greater than the amplitudes shown on the curves computed by integration.

At first sight there should be no problem in constructing envelopes showing the limiting values of acceleration-velocity and displacement when plotted against period. This is actually true except that it is laborious to apply the foregoing acceleration-formula perhaps several hundred times in a comprehensive study if it can be avoided. A disadvantage also lies in the fact that, if the acceleration, velocity, and displacement envelopes are drawn independently, it is often difficult to recognize some peculiar feature of one envelope on both of the others. This was true to some extent in the envelopes constructed in the analysis of the records of the destructive El Centro Earthquake of May 18, 1940.

The use of a graphical method of applying the simple harmonic motion formula [$a = (4\pi^2 A/T^2)$] eliminates the need for any computation and at the same time yields acceleration-velocity and displacement envelopes which are wholly consistent with each other. The graph is simple to make, requiring nothing more than a few straight lines drawn on double logarithmic paper. This simplicity results from the fact that the formula is basically of parabolic form and a straight line drawn across the cross-section paper represents either a parabola or hyperbola depending on the inclination of the lines (see Fig. 2). One system of diagonal coordinates can thus be constructed for acceleration and another for velocity, making four arguments in all on a single graph. For the diagonal systems of coordinates it is only necessary to draw the boundary-lines marking the limits of each cycle and to construct a paper logarithmic scale to interpolate between them.

In practice, readings from the original acceleration-curves and from the computed velocity and displacement are plotted directly on the graph without any computation whatsoever. An envelope embracing the plots is a true envelope for three elements of motion and may be used as such. Since the reading of logarithmic scales, however, is not as simple as a linear scale and since the relative magnitudes of various points on the graph are not shown in simple proportion, it is desirable that envelopes on linear scales be constructed by making a sufficient number of readings along the logarithmic envelope and constructing the linear-scale envelopes. The resulting acceleration-, velocity-, and displacement-envelopes must necessarily be consistent with each other as they are all measured from the same curve. A peculiarity on one curve will always be carried through the two corresponding envelopes.

In the current work the envelopes have been reproduced on the linear scales in the exact form in which the composite envelope appears on the logarithmic graph. Thus, in addition to showing the maximum amplitudes, the linear scales show other limitations of the plotted data which conflict with the definition of an envelope as constituting a locus of maximum values. This situation will be clear from an inspection of Figure 4. It is felt, however, that it is desirable to retain the form in which the curve is originally developed as it furnishes a means by which any special characteristics of the curves can be easily followed through on all three envelopes--acceleration, velocity, and displacement. A linear-scale envelope drawn to show only maximum values will

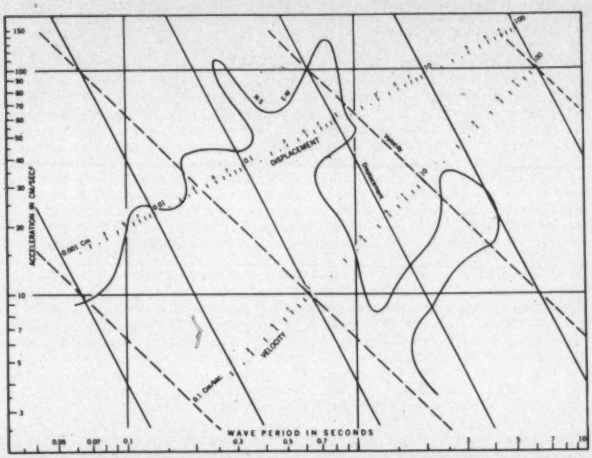

Fig. 2--Period-amplitude graph, derived from Vernon (Los Angeles) accelerograph record of Long Beach earthquake of March 10, 1933, horizontal motion, epicentral distance 33 miles, showing logarithmic scales for period, acceleration, velocity, and displacement (Actual graph drawn on double logarithmic paper, interpolations between diagonal lines made with auxiliary paper scales)

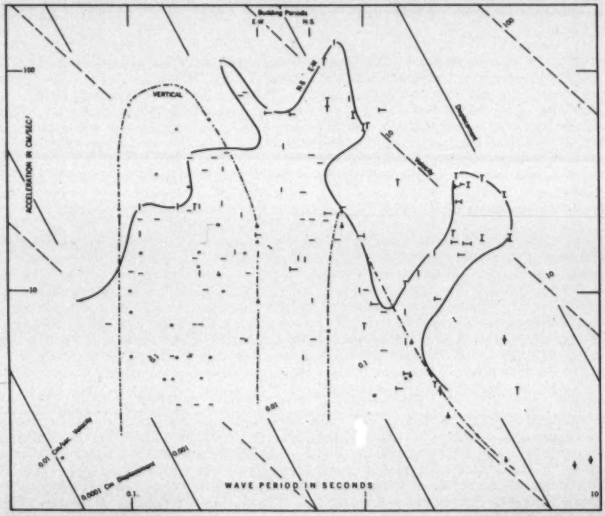

Fig 3--Period-amplitude graph, derived from record as in Figure 2, showing data plotted from acceleration-, velocity-, and displacement-curves similar to those in Figure 1 (solid line = horizontal components, dot-and-dash line = vertical component)

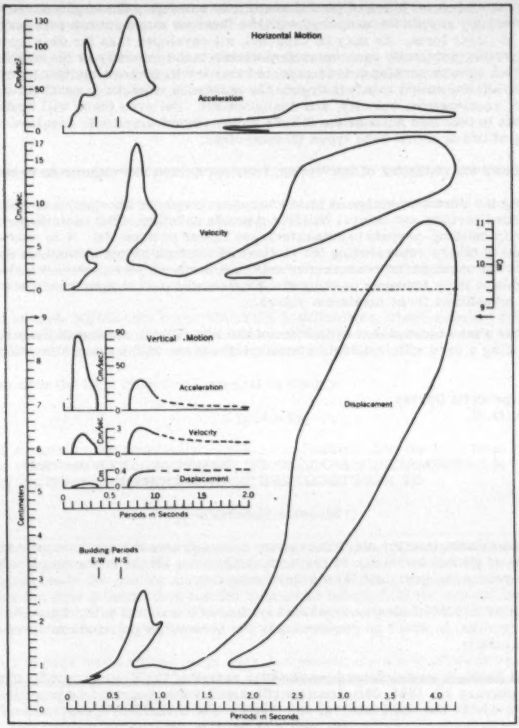

Fig. 4--Period-amplitude envelopes drawn to linear scales, Vernon, Long Beach earthquake of March 10, 1933, derived from boundary-curve shown in Figure 3

necessarily contain, rather frequently, sharp discontinuities which appear somewhat of a novelty at this time but are nevertheless quite in order.

Figure 3 shows the plots on which the envelope for the Vernon record of March 10, 1933, is based. Readings from the original acceleration-curve are indicated by short vertical lines for the north-south component, similar horizontal lines for the east-west component, and single dots for the vertical. The addition of a single short line to either one signifies a reading from a velocity-curve; the addition of two signifies a reading from a displacement-curve.

The drawing of envelopes around the plots is a matter of judgment and may be modified depending upon the requirements and scope of each individual problem.

In all cases it is essential that separate envelopes be drawn for vertical motion, but in the case of horizontal motion the separation of the two components is optional depending upon the nature of the instrument-foundation. The two components of a ground-record often have such similar envelope-characteristics that little is to be gained by separating them. On the other hand, the records obtained at the top of a tall building are often so dissimilar that separate envelopes are mandatory.

In studying the characteristics of period-amplitude envelopes the single curve in the logarithmic form is pleasingly simple as compared with the three or more curves necessary to represent the same thing in linear form. As may be expected, all envelopes thus far developed show different features depending primarily upon epicentral distance and intensity of the shock. After a sufficient accumulation of such envelopes it is expected that it will be possible to construct "master" envelopes which will represent to a fair degree the maximum expectable earthquake-motions in terms of period, acceleration, velocity, and displacement. But even these will have to be augmented somewhat to take into account the failure of any period-amplitude envelope to provide for the superposing of two or more wave types on each other.

Figure 4 shows the reduction of the Vernon envelopes from logarithmic to linear form.

In examining the Vernon envelope it is of interest to compare the amplitudes at the points where the recorded periods and natural building-periods coincide. The coincidence of maximum accelerations with building-periods is not perfect, yet rather pronounced. It is characteristic of this envelope and of others representing the motions of the tops of tall structures that the maximum accelerations do not occur at the resonance-points, but fairly close to them. Another characteristic of many envelopes is their tendency to show two zones on the period-spectrums where the motions rise to two and sometimes three maximum values.

In conclusion it may be said that utilization of the logarithmic method of constructing envelopes is providing a very efficient tool in accomplishing one of the many aims of engineering seismology.

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A MATHEMATICAL ANALYSIS OF NUMERICAL INTEGRATION OF ELECTROMAGNETIC SEISMOGRAMS

Florence Robertson

GALITZIN has shown that for electromagnetic seismograms the earth-motion may be expressed in terms of (1) the derivative of the trace-amplitude, (2) the trace-amplitude, (3) the first integral, (4) the second integral, and (5) the third integral.

Now NEUMANN has developed an ingenious method of numerical integration for use on accelerometer-records, in which he required only the second integral and his results have been verified experimentally.

The original problem was to determine the true nature of the S-wave motion of the Peruvian Earthquake of February 29, 1944, 03^h, from the Florissant seismograms by extending NEUMANN'S method so as to evaluate the third integral and thereby use GALITZIN'S expression for the earth-motion.

When I first attempted to evaluate the three integrals numerically for the Peruvian Earthquake, two serious difficulties arose: (1) My resulting curves could be made to take on strange shapes by making only slight changes in the value of the so-called constants of integration; and (2) many of the oscillations in the original curve disappeared from the graphs of the second and third integrals.

Now any method of numerical integration is admittedly a process of approximation. And the smaller Δt, the closer the approximation. However, if we are to combine the first, the second, and the third integrals for successive instants of time, it is imperative that there be nothing in the process of integration which will make such a combination ambiguous or impossible.

NEUMANN has emphasized that any errors present in the original trace-amplitudes as a result of the indeterminateness of the true axis of oscillation are cumulative in the process of numerical integration and that these errors must be taken into account in the evaluation of the second integral. He used an empirical method of determining the necessary correction-factors (parabola).

The writer was also cognizant of WALTER'S conclusion that the resulting error-curve for the third integral is a cubical parabola. Furthermore, it seemed obvious to the writer that errors from any source, such as the incorrect determinations of the constants of integration, were cumulative.

For these reasons, it was decided to examine analytically the method of numerical integration to see if there is anything inherent in the method that would cause the observed effects.

For this purpose, it was assumed that the seismogram-trace was a simple sine-wave, such as is often observed during the surface waves of a normal earthquake or during large microseisms, and that the causing earth-motion was, at least, harmonic. By assuming that the trace-motion is given by

$$y = \sin \omega t \tag{1}$$

the analytical expressions for the first, the second, and the third integrals are easily obtainable.

For the numerical integrals the same results are not so easily obtained. For the purpose of this investigation two time-increments were used:

(1) $\Delta t = 1$ second, because of its convenience.
(2) $\Delta t = 1/4$ second, because this seemed to the writer to be the smallest value of Δt compatible with accuracy of the time-data of teleseismic records.

In order to exclude NEUMANN'S and WALTER'S difficulties, which resulted from the fact that the true axis of oscillation was unknown, the values of the trace-amplitude were computed; using a table of trigonometric functions, for successive instants of time.

From these data the first numerical integral is simply

$$\Sigma y_1 \Delta t = x_{3i} \tag{2}$$

Now numerical integration automatically imposes the condition that the first term of the first integral will be zero when $t = 0$ if the original trace-amplitude is zero when $t = 0$. Imposing this condition on our analytical integral we obtain

$$x_{3i} = (1/\omega)\,(1 - \cos \omega t) \tag{3}$$

The graph of this equation is shown in Figure 1 as the solid line. The corresponding numerical integral, for $\Delta t = 1$ second, is shown as the dashed curve. From these curves we see: (1) The numerical integral leads the true or analytical curve; (2) the inflection-points are greater, in absolute value, for the true integral than for the numerical integral (3) the axes of both curves are translated with respect to the original time-axis. Now for use in GALITZIN'S equation this phase-difference and translation of the axes are intolerable.

Since $\Delta t = 1$ second was a rather large time-increment, the above process was repeated using $\Delta t = 1/4$ second. The graph of $\Sigma y \Delta t$, when $\Delta t = 1/4$ second, is shown in Figure 2 as the dashed line together with graph of the corresponding analytical equation

$$x_{3i} = (1/\omega)\,(1 - \cos \omega t) \tag{3}$$

which is shown as the solid line. While the differences noted in Figure 1 are decreased, nevertheless, they are still present.

By using a second approximation for the numerical integral, that is,

$$x_{3i} = \Sigma y_1 \Delta t - (1/2)\,(\Sigma y_1 \Delta t - \Sigma y_{i-1} \Delta t) \tag{4}$$

the phase-difference is eliminated. These values are shown as the circled points in both Figures 1 and 2 for $\Delta t = 1$ and $1/4$ second, respectively.

The translation of the axes of oscillation of the integral curves results from the fact that we imposed the condition that $x_{3i} = 0$ when $t = 0$. This, however, is contrary to our assumption of harmonic motion such that the trace-amplitude is zero when $t = 0$. For harmonic motion, since $y = 0$ when $t = 0$, the first integral must be a maximum when $t = 0$. This gives for the constant of integration

$$C_1 = x_{3max} + (1/\omega) \tag{5a}$$

and therefore

$$x_{3i} = -(1/\omega)\cos\omega t + C_1 = -(1/\omega)\cos\omega t + [x_{3max} + (1/\omega)]$$

Now this equation defines a whole family of curves, depending only on the value of x_{3max}. But the necessary and sufficient condition that the resulting integral curve be symmetrical with respect to the same axis as the original curve is that $C_1 = 0$. Imposing this condition on our expression for the displacement, we find that the maximum earth-displacement is

$$x_{3max} = -(1/\omega) \tag{5b}$$

the negative reciprocal of the angular velocity. Whence, for the true or analytical curve, the earth-motion is

$$x_{3i} = -(1/\omega)\cos\omega t_i \tag{6}$$

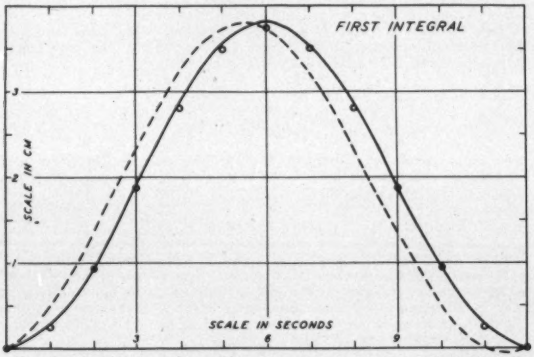

Fig. 1--Graphs of equation (3) and of numerical integral (dashed line)

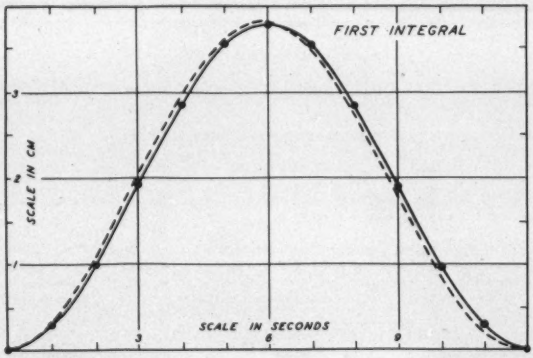

Fig. 2--Graphs of $\Sigma y\Delta t = 1/4$ second (dashed line) and of equation (3)

a negative cosine-function, the amplitude of which is the reciprocal of the angular velocity.

Now we must impose on the numerical integral the conditions of harmonic motion in which there will be no translation of the axis of oscillation with respect to the original time-axis. The fact that, for the true integral, when $C_1 = 0$, the maximum displacement is the negative of the value of C_1 determined under the conditions automatically imposed by numerical integration, that is, $y = 0$ when $t = 0$ and $x_3 = 0$ when $t = 0$, shows us that the conditions of harmonic motion are imposed if we add algebraically to the earth-displacement the negative of the constant of integration determined under the conditions imposed by numerical integration. For the analytical integral this constant is the reciprocal of the angular velocity.

For the numerical integral this constant must be determined empirically. NEUMANN uses as his first approximation for this quantity the arithmetic mean of $\Sigma y\Delta t$

$$C'_{m_1} = (\Sigma y\Delta t/n) \qquad (7)$$

The graph of $(\Sigma y\Delta t - C'_{m_1})$ is shown as the dashed curve in Figure 3 together with the graph of

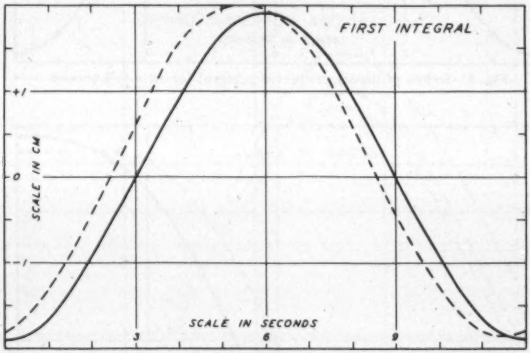

Fig. 3--Graphs of $\Sigma(y\Delta t = C'_{m_1})$ [dashed line] and of equation (6)

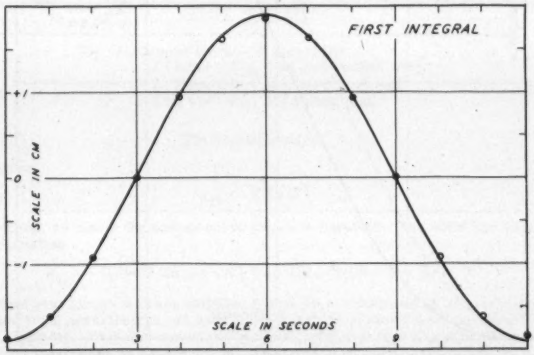

Fig. 4--Graph of finally corrected integral for $\Delta t = 1$ second

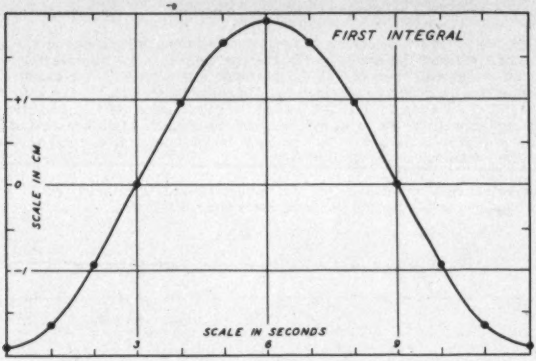

Fig. 5--Graph of finally corrected integral for $\Delta t = 1/4$ second

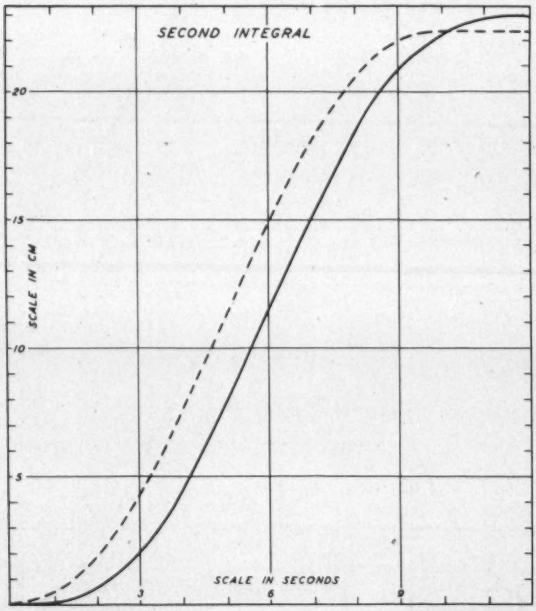

Fig. 6--Graphs of equation (10a) when $\Delta t = 1$ second (dashed line) and of analytical equation (10b)

$x_{3i} = -(1/\omega)\cos\omega t$. We see that C'_{m_1} is too small since the inflection-points of the numerical curve are greater, algebraically, than these for the analytical curve.

It has been found that the axes of the two curves can be made to coincide if we use

$$C'_1 = (1/2)\,(\Sigma y\Delta t_{max} - \Sigma y\Delta t_{min}) \tag{8}$$

instead of the arithmetic mean.

In Figures 4 and 5 the circled points are the finally corrected values of the numerical integral for $\Delta t = 1$ second and 1/4 second, respectively, that is,

$$x_{3i} = \Sigma y_i\Delta t - (1/2)\,(\Sigma y_i\Delta t - \Sigma y_{i-1}\Delta t) - C'_1 \tag{9}$$

In Figure 5 the agreement between the computed values and the true integral is excellent. In Figure 4, where $\Delta t = 1$ second, the inflection-points are somewhat less for the numerical curve than for the analytical curve.

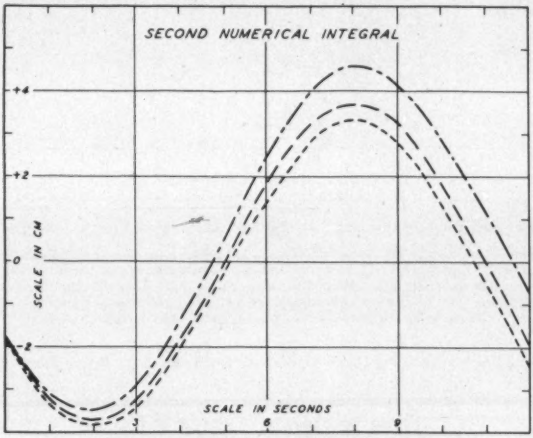

Fig. 7--Graphs for $\Delta t = 1$ second for
$\Sigma(\Sigma y\Delta t - C'_{m_1})\,\Delta t$ [dot-dashed line],
$\Sigma(\Sigma y\Delta t - C_1)\,\Delta t$ [dotted line], and
$\Sigma(\Sigma y\Delta t - C'_1)\,\Delta t$ [dashed line]

The second integral

If we compute

$$x_{4i} = \Sigma\Sigma y\overline{\Delta t}^2 \tag{10a}$$

when $\Delta t = 1$ second, we obtain the dashed curve shown in Figure 6. The solid line is the graph of the analytical equation

$$x_{4i} = -(1/\omega^2)\sin\omega t + C_1 t = -(1/\omega^2)\sin\omega t + (1/\omega)\,t \tag{10b}$$

This tells us that even though we have satisfied the physical conditions of harmonic motion by making $x_{4i} = 0$ when $t = 0$, nevertheless, we have automatically included something more in our double summation of $\Sigma\Sigma y\Delta t^2$. That this something is the value of that first constant of integration is proven to be true because we can eliminate the slope of the axis of the numerical integral by summing the corrected values of the first integral.

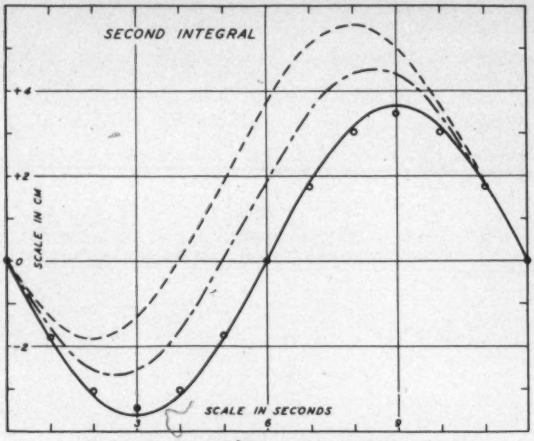

Fig. 8--Graphs of $\Sigma[\Sigma y_i \Delta t - (\Sigma y_i \Delta t - \Sigma y_{i-1})] \Delta t - C_1 t$ [dot-dashed line], of equation (11) [dashed line], and of equation (12)

In Figure 7 we have for $\Delta t = 1$ second: (1) The dot-dashed curve $\Sigma(\Sigma y \Delta t - C'_{m_1}) \Delta t$--note that its axis slopes upward; this is what we should expect since C'_{m_1} was found to be too small; (2) the dotted curve $\Sigma(\Sigma y \Delta t - C_1) \Delta t$--note that its axis slopes downward; this is most interesting since C_1 is the value of the analytical constant of integration, but it is too large for use with a finite number of observations; (3) the dashed curve $\Sigma(\Sigma y \Delta t - C'_1) \Delta t$. This is the double summation of the first numerical integral in which its axis was translated by the amount $C'_1 = (1/2)(\Sigma y \Delta t_{max} - \Sigma y \Delta t_{min})$.

For the purpose of Figure 7, the phase-corrections found necessary have not been made be-

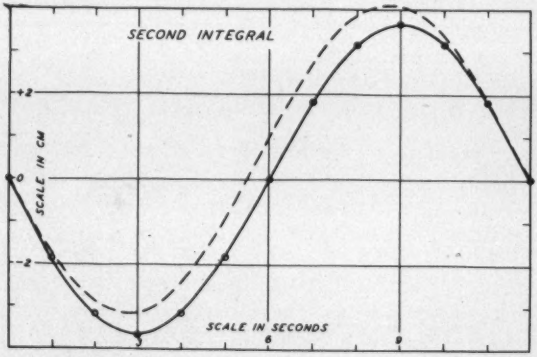

Fig. 9--Graphs of $\Sigma\Sigma y_i t^2 - C_1 t$ for $\Delta t = 1/4$ second (dashed line) and for $\Delta t = 1$ second

cause the purpose of these curves is to investigate only the influence of the first constant of integration. We find (1) that there is one, and only one, value which prevents a slope in the axis of oscillation, and (2) the beginning conditions imposed are that $x_4 = C'_1$ when $t = 0$ and not those of harmonic motion. Hence if we determine the second numerical integral from the corrected values of the first numerical integral by a direct summation-process, we must translate the axis in such a way as to make $x_{4i} = 0$ when $t = 0$, that is, by an amount C'_1. This is equivalent to

$$x_{4i} = \Sigma(\Sigma y\Delta t - C'_1)\,\Delta t + C'_1 \cdot = \Sigma\Sigma y\Delta t^2 - nC'_1\,\Delta t + C'_1\,\Delta t$$

$$= \Sigma\Sigma y\overline{\Delta t}^2 - C'_1\,(n\Delta t - \Delta t) = \Sigma\Sigma y\overline{\Delta t}^2 - C'_1\,t \qquad (11)$$

The graph of x_{4i} so determined is given in Figure 8 as the dashed line. The most noticeable features of this curve are (1) that it is asymmetrical with respect to the original time axis and (2) that it

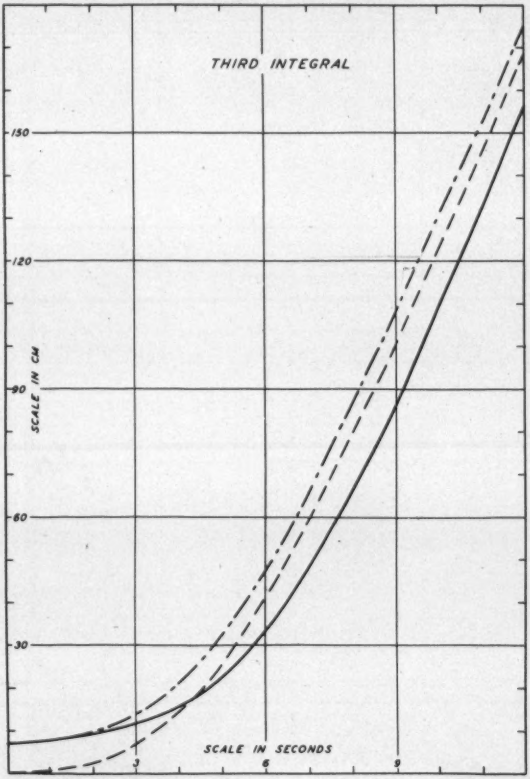

Fig. 10--Graphs of $\Sigma\Sigma\Sigma\, y_i\, \overline{\Delta t}^3$ for $\Delta t = 1$ second (dashed line), of $\Sigma\Sigma\Sigma\, y_i\, \overline{\Delta t}^3$ for $\Delta t = 1$ second with its axis translated by $(C_1')^3$ [dot-dashed curve), and of analytical equation (13)

leads the true or analytical curve, $x_{4i} = -(1/\omega^2) \sin \omega t$, which is shown as the solid line.

If, however, we use for the numerical integration the values of the first integral corrected for the phase-shift seen in Figure 1, that is,

$$\Sigma[\Sigma y_i \Delta t - (1/2)(\Sigma y_i \Delta t - \Sigma y_{i-1} \Delta t)] \Delta t - C_1 t$$

we obtain the dot-dashed curve shown in Figure 8.

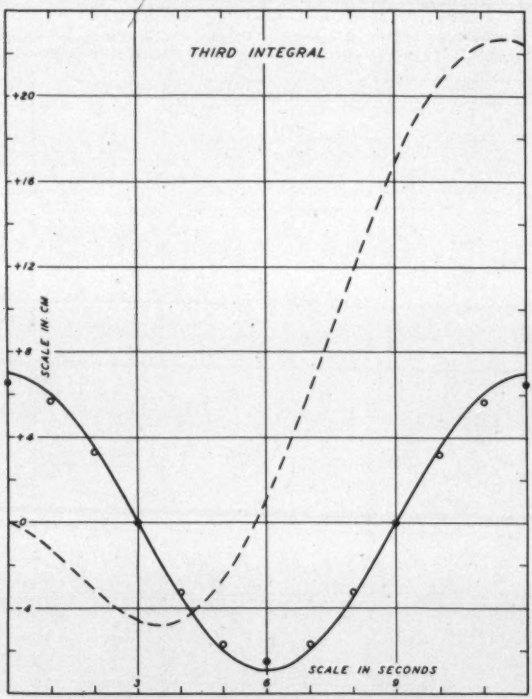

Fig. 11--Graphs of third integrals for $\Delta t = 1$ second of true integral and of axis translated by C_3 (dashed line)

This curve seems to suggest that the remaining phase-difference observed between the numerical integral and the analytical integral curves is due to the approximations involved in the process of numerical integration. If we apply a phase-correction factor similar in form to the one used for the first integral, we obtain the circled points shown in Figure 8, that is,

$$x_{4i} = \Sigma[\Sigma y_i \Delta t - (1/2)(\Sigma y_i \Delta t - \Sigma y_{i-1} \Delta t) \Delta t] - (1/2)(\Sigma \Sigma y_i \Delta t^2 - \Sigma \Sigma y_{i-1} \Delta t^2) \text{ corrected } -C_1 t \qquad (12)$$

This does eliminate the phase-differences; but the inflection-points are less for the numerical integral than for the true integral.

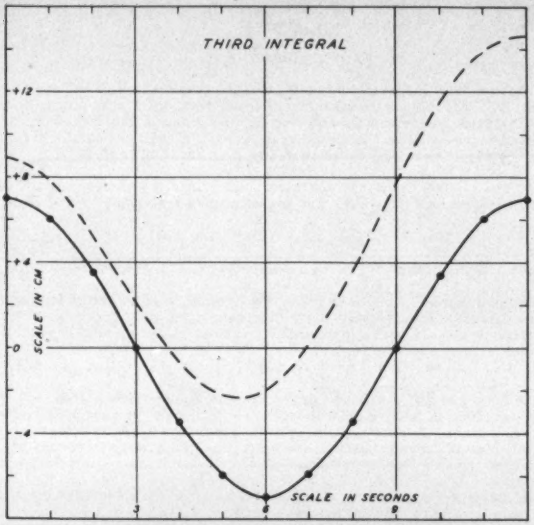

Fig. 12--Graphs of third integral for $\Delta t = 1/4$ second of true integral and of axis translated by C_3' (dashed line)

In Figure 9, we have the graphs for $\Delta t = 1/4$ second for

$$\Sigma\Sigma y_i t \; - C'_1 t$$

shown as the dashed line and the values corrected as for $\Delta t = 1$ second shown as the circled points. Here the computed points do, for practical purposes, coincide with the analytical curve.

The third integral

In Figure 10 we have shown as the dashed line the direct or triple summation $\Sigma\Sigma\Sigma y_i \overline{\Delta t}^3$ where $\Delta t = 1$ second. The corresponding analytical curve, the solid line, is

$$x_{5i} = (1/\omega^3) \cos \omega t + (1/2)\, C'_1 t\, (t + 1) \qquad (13)$$

The dot-dashed curve in Figure 10 is simply $\Sigma\Sigma\Sigma y \overline{\Delta t}^3$ with its axis translated by the amount $(C'_1)^3$.

We saw, from the second numerical integral, that the first constant of integration was automatically included by the term $C'_1 t$ in the second summation-process. Consequently, if we compute the triple summation, we include in the process

$$\Sigma(C'_1 t) = C'_1 \; \Sigma t = (1/2)\, C'_1 t\, (t + 1) \qquad (14)$$

In other words, we have

$$\Sigma\Sigma\Sigma y_i \overline{\Delta t}^3 \text{ equivalent to } \iiint y dt^3 + (1/2)\, C'_1 t\, (t + 1)$$

This is very interesting. If we had merely considered the indefinite triple integral of y, we would have had

$$x_{5i} = (1/\omega^3) \cos \omega t + (1/2)\, C_1 t^2 + C_2 t + C_3 \qquad (15)$$

But for the true integral under the conditions of harmonic motion in which there is no translating of the axes, C_1, C_2, and C_3 are each zero. Whence

$$x_{5i} = (1/\omega^3) \cos \omega t \qquad (16)$$

In order that the third numerical integral correspond to the true or analytical integral, we must subtract from $\Sigma\Sigma\Sigma y\overline{\Delta t}^3$ the contributions made by the first constant of integration, that is, $(1/2)\, C'_1 t\, (t + \Delta t)$ from each computed value of the displacement. Furthermore, the axis of the third numerical integral must be translated by the amount of the third constant of integration C'_3. Theoretically C'_3 should equal C'_1 cubed; actually it is found to be $(1/2)\, [x_{5max} - x_{5min}]$.

Figures 11 and 12 show the third integrals for $\Delta t = 1$ and 1/4 second, respectively. Here also the solid curves are the true integrals. The dashed curves are simply

$$\Sigma\Sigma\Sigma y\overline{\Delta t}^3 - (1/2)\, C'_1 t\, (t + \Delta t)$$

that is, the axes are still translated by the amounts C_3 and C'_3, respectively.

The circled points were obtained by taking the summation of the terms for the second integral which had been corrected for the phase-shift; then subtracting $(1/2)\, C'_1 t\, (t + \Delta t)$ from each sum, and finally introducing as a fourth approximation a further phase-correction of the form

$$(1/2)\left\{ [\Sigma x_{4i} \Delta t - (1/2)\, C'_1 t\ (t_1 + \Delta t)]\, [\Sigma x_{4i-1} \Delta t - C'_1 t_{1-1}\, (t_{1-1} + \Delta t)] \right\}$$

That is, for the third integral the phase-correction must be determined from the data after the effect of the first constant of integration has been removed. This requirement contrasts strongly with the preceding cases. For the first integral the procedure for determining the phase-correction was immaterial. For the second integral, the phase-correction was determined before removing the influence of the first constant of integration.

From this analysis it seems to be clear that (1) a part of the difficulties encountered by the writer in the numerical integration of the Peruvian Earthquake records was due to the choice of too large a time-increment, (2) that other difficulties encountered by the writer in common with other workers in the field are inherent in the method of numerical integration, and (3) that these difficulties will diminish in proportion to the degree of closeness of approximation attained. In other words, difficulties will always exist (1) because numerical integration is inherently an approximation-process and (2) all errors are cumulative.

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AN ELECTRONIC EARTHQUAKE-RECORDER

F. Keller

For almost five years, an amateur seismographic station which has recorded nearly all of the earthquakes that have been listed by the United States Coast and Geodetic Survey has been in continuous operation at New Kensington, Pennsylvania. The apparatus used in this station is jerry-built, yet it has some features which may be of interest to seismologists. Of particular interest are the electronic devices employed for amplifying and recording seismic waves. The new features are the circuits of the photocell pick-up and amplifier and the electrical recorder.

At first, a rather large seismograph of the Bosch-Omori type was constructed and magnification was obtained by the customary mechanical-lever arrangement. It soon was apparent that friction limited the usable magnification to about 20 times and that at most only nearby and heavy shocks would be recorded. Thus, it was concluded that a high-magnification system would be required to make the operation of an amateur station of more than passing interest. This indicated registration on photographic paper would have to be employed. Photographic registration, however, is uninteresting and rather inconvenient and expensive to operate. An electrical recorder which would trace a visible record on a smoked-paper chart seemed the logical solution to this problem; consequently, the development of a suitable electrical recorder was undertaken. A seismographic recorder of this character had been described by HALLEY WOLFE [see 1 of "References" at end of paper] but this recorder was constructed for battery-operation with separate batteries for the

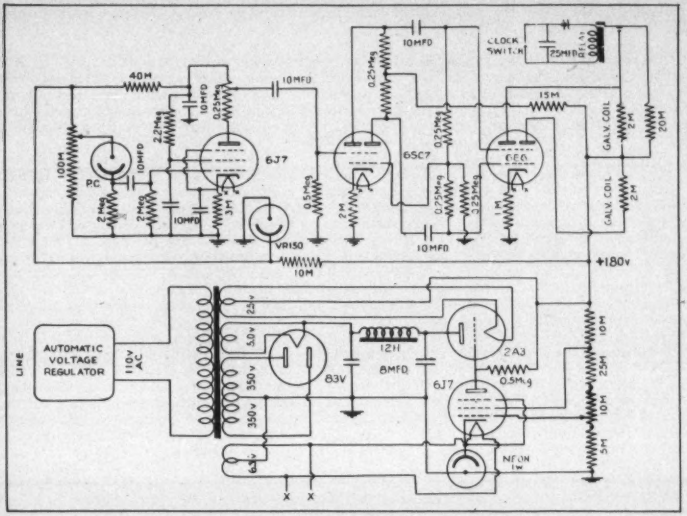


Fig. 1--Wiring diagram of photocell, amplifier, and power-supply circuits

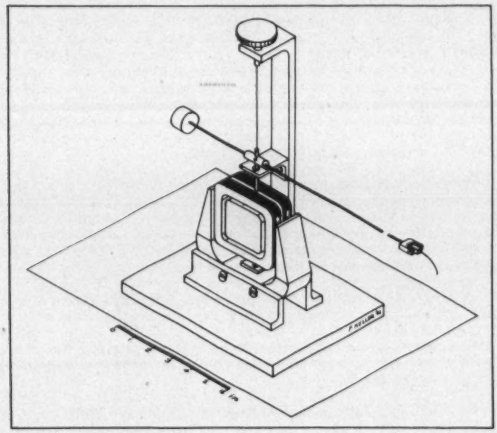


Fig. 2--Details of recorder

galvanometer-lamp, the photocell, and the amplifier-circuits in order to obtain constant illumination and uniform plate- and filament-voltages.

The new recorder was designed in accordance with the general principles outlined by WOLFE with some modifications to provide more convenient and economical operation. This recorder is operated by alternating current and employs an entirely different circuit for the electronic amplifier. Furthermore, it was necessary to provide some means for overcoming the usual fluctuations in the galvanometer-lamp and the amplifier-current supply when ordinary house-current was used.

The complete circuits of the amplifier and power-supply are shown in Figure 1. The amplifier contains three separate circuits, namely, a photocell-and-preamplifier circuit, a self-balancing phase-inverter circuit, and a one-stage push-pull amplifier-circuit. Entirely satisfactory voltage-regulation was obtained by using a Thordarson automatic voltage-regulator of 100 volt-ampere rating which controls the input-voltage to within about plus or minus one per cent for the galvanometer-lamp and the amplifier and by incorporating a regulated power-supply [2] in the amplifier. The latter was necessary to avoid changes in voltage because of the interaction of the several circuits. Since the photocell and the three stages of the amplifier all draw current from the same source, a VR150 voltage-regulator tube was added between the preamplifier and the phase-inverter circuits.

In operation, the amplifier is excited by a small beam of light reflected from the mirror of the galvanometer that is connected with the seismometer. Thus, a frictionless connection is had between the seismometer and the recording system. The photocell is covered with a shield that has a 3/8 by 3/4 inch opening to admit light from the galvanometer-mirror. Illumination from the mirror is adjusted so that only about half of the rectangular light-spot impinges on the sensitized surface of the photocell. In the present amplifier, a Cetron photocell with a relatively large sensitized surface is used. The polarizing voltage on the cell is slightly less than 90 volts.

When the mirror rotates, a larger or smaller area of the sensitized surface of the photocell will be illuminated and the output of the photocell will vary directly with the area that is illuminated providing illumination is of uniform intensity and will produce a proportional change in the output of the amplifier. These variations in output are utilized to operate the electrical recorder which is actually a large galvanometer that has a coil with two windings which are connected in the two plate-circuits of the push-pull stage of the amplifier.

The construction of the electrical recorder that writes the record on the smoked-paper chart is shown by Figure 2. On this recorder, the coil contains two windings on a 3-inch by 3-inch frame, each having about 2000 turns of No. 40 DSC wire and a resistance of about 2000 ohms. This coil is suspended in the field of a large Alnico magnet by a three-inch suspension of 0.025-inch diameter, nichrome wire and is restrained from lateral movement by ring-bearings. The suspension should have just sufficient torque to overcome the friction of the recording stylus on the smoked paper. A hinged stylus is attached to the end of a 15-inch counterbalanced arm that is fastened to the rotating element of the recorder. The stylus for recording on smoked paper can be replaced by a pen for recording with ink with very satisfactory results.

When the spot of light remains stationary on the photocell, the currents in the two coils exert equal and opposite torques; consequently, no deflection of the writing arm will occur. When the spot of light moves, however, as a result of rotation of the galvanometer or seismometer-mirror, the alternating currents in the recorder-coils will be 180° out of phase with resultant in-phase torques which will cause the writing-arm to deflect. The amount of deflection will be proportional to the deflection of the galvanometer or seismometer-mirror.

Very good response to both short- and long-period teleseisms has been obtained with this amplifier and recorder. The response to the usual long-period waves is obtained principally through the use of large-capacity condensers in the various circuits. With these electronic devices, the response and wave-form obtained compare favorably with those obtained with the usual observatory-equipment. Examples of the type of records obtained with the recording equipment that has been described are illustrated by Figure 3.

Various units of the apparatus at the New Kensington Station are installed in a 6-foot by 12-foot room in the basement of a residence where they are free from local disturbances. The general plan of the station is shown by Figure 4. The seismometer rests on a pier that goes through the concrete floor and is anchored to a shale formation about 18 inches below the floor-level. Arrangement of the various electrical units and accessory equipment is illustrated by Figure 5.

At present, the seismometer in use is of the electromagnetic type much like the Wenner instrument but the design has been simplified considerably to eliminate as much machine work as possible. The main change is in the type of suspension that is used. For the upper hinge, a tandem arrangement of two hard brass-foil strips is used; whereas, the lower hinge consists in the ordinary pivot and jewel-cup bearing. The seismometer-coil contains 250 turns of No. 32 enameled wire and has a resistance of about 14 ohms. With proper assembly of the upper hinge, it has been possible to obtain periods of 10 to 15 seconds with very good stability. The general design of the seismometer is indicated by Figure 6.

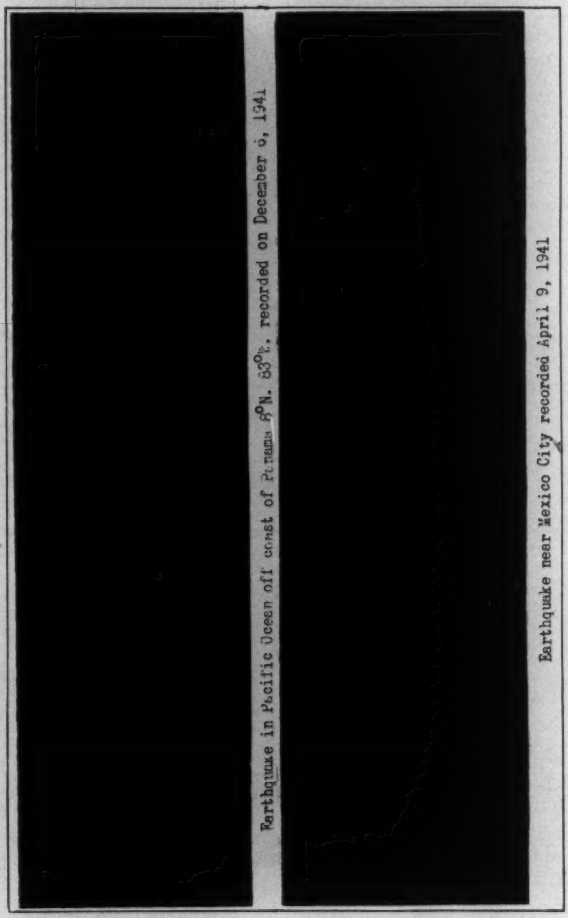

Earthquake in Pacific Ocean off coast of Panama 8°N. 83°W., recorded on December 6, 1941
Earthquake near Mexico City recorded April 9, 1941

Fig. 3--Type of seismogram obtained with electronic earthquake recorder

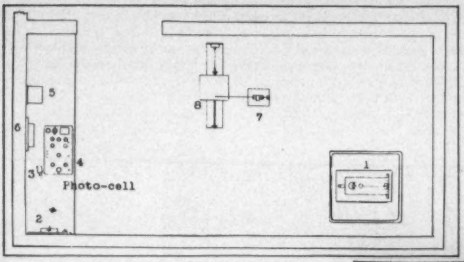


Fig. 4--Plan of New Kensington seismographic station (1, Seismometer; 2, galvanometer; 3, lamp; 4, amplifier; 5, automatic voltage-regulator; 6, telechron timer; 7, recorder; 8, recorder-drum

Fig. 5--Galvanometer, amplifier, voltage-regulator, and telechron timer

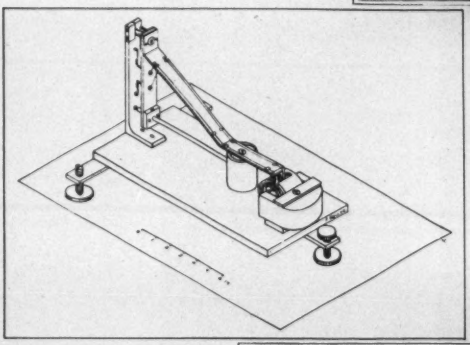


Fig. 6--Details of seismometer

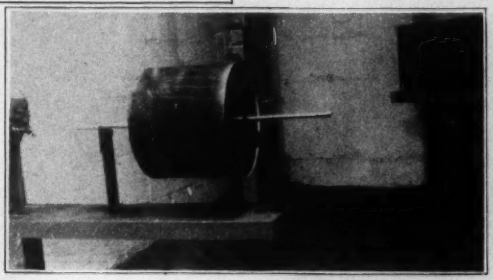


Fig. 7--Recorder-drum and electrical recorder

The seismometer-coil is connected to a long-period galvanometer (Leeds and Northrup Type P) in a shunt-circuit like that used in the Wenner system in order to obtain suitable damping. This arrangement is conventional and could be employed for registration on photographic paper if desired.

Recording is done on a smoked-paper chart, 8-1/2 inches by 33 inches, which is mounted on a 10.2-inch diameter drum as shown by Figure 7. This drum is turned by a four-watt electric-chart clock and it revolves once every half hour with a chart-speed of a little more than one inch per minute. Fastbrite-E copy paper is used for the charts which are fixed by dipping them in an alcohol-shellac mixture. Translation of the drum is obtained with a left-handed lead screw that has eight square threads per inch.

Time-control is obtained by means of a Telechron clock which has a mercury switch connected with the long-sweep second-hand. This switch actuates a relay which shunts a resistance across one of the plate-coils of the electrical recorder for about two seconds each minute. This causes a slight deflection of the writing arm and records a time-mark on the chart. The clock is checked twice daily with radio time-signals from station WWV. The time-marks in general are accurate to within about 0.05 minute. It is realized that it is not desirable to have both the recording-drum motor and the clock operating from the same power-source. It is planned, therefore, to obtain a weight-driven pendulum regulator for making time-marks which will be independent of the electrical system.

At the present time, the seismometer and galvanometer are operated at periods of eight and ten seconds, respectively, and the damping-ratio obtained with the shunt-circuit is about 0.5. The total magnification of the system is of the order of 500 times, although a magnification of 1500 times or more can be obtained readily. With higher magnifications, however, microseisms become troublesome. The magnification can be changed by several means, as for instance, changing the length of the light-lever, increasing or decreasing the intensity of the illumination, or by adjustment of the gain-controls on the amplifier. Only a small amount of light is needed for recording. This is obtained from a six- to eight-volt radio pilot-lamp that is operated at about five volts to obtain long life. The amplifier has been in operation for five years and only three of the tubes have required replacement. The complete electrical set-up requires less than 100 watts for continuous operation.

With reasonably well-made and adjusted equipment of the type described, it is felt that visible records of both near and distant earthquakes can be obtained with a quality comparable with those made by photographic registration. The recorder is useful also in obtaining visible records of galvanometer- and seismometer-tests and in establishing the various conditions for obtaining satisfactory damping.

In conclusion, it is considered that electronic amplifying and recording devices can be used to advantage for the magnification and recording of earth-motion, especially where photographic methods would not be convenient or economical.

The author wishes to acknowledge the helpful suggestions of Dr. H. LANDSBERG, DONALD C. BRADFORD, and the information on the HALLEY WOLFE recorder that was obtained by correspondence with Dr. H. BENIOFF.

References

[1] HALLEY WOLFE, A seismographic recorder, Rev. Sci. Inst., v. 5, p. 359, 1934.
[2] Automatic voltage regulator, Radio Amat. Handbook, p. 195, 1940.
[3] A self-balancing phase-inverter circuit, R. C. A. Mfg. Co., Appli. Note No. 97, September 28, 1939.

New Kensington, Pennsylvania

THE SEISMOLOGICAL INSTALLATION AT THE SOUTH DAKOTA STATE SCHOOL OF MINES AND TECHNOLOGY, RAPID CITY, SOUTH DAKOTA

H. E. McComb, R. E. Gebhardt, and David Wark

In 1938, Professor E. L. TULLIS, head of the Geology Department at the South Dakota State School of Mines and Technology at Rapid City, South Dakota, requested information and specifications from the United States Coast and Geodetic Survey on piers and rooms for a seismological in-

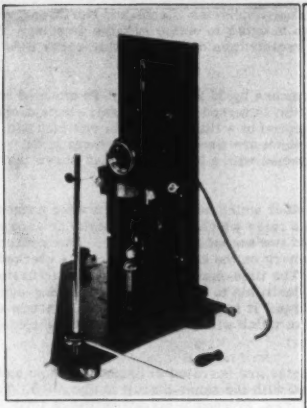


Fig. 1--Wood-Anderson seismometer, cover removed

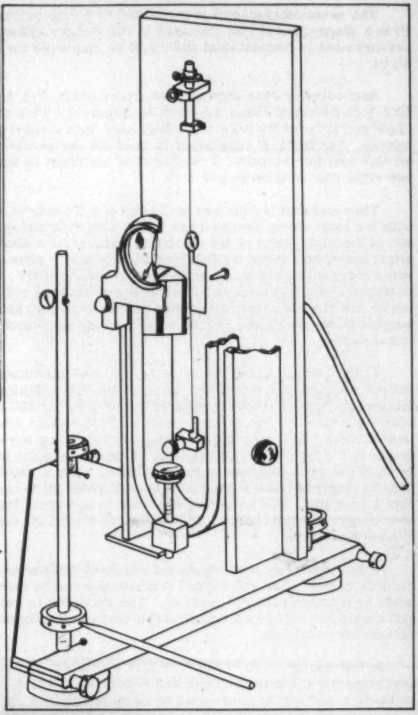


Fig. 2--Sketch showing relative locations of damping magnets, vane, and nozzle

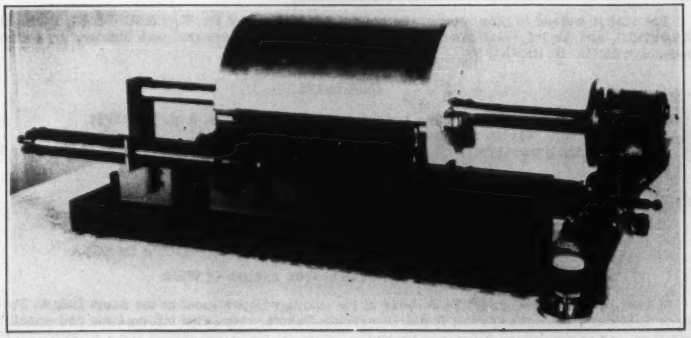


Fig. 3--Miller recorder with light-shield removed

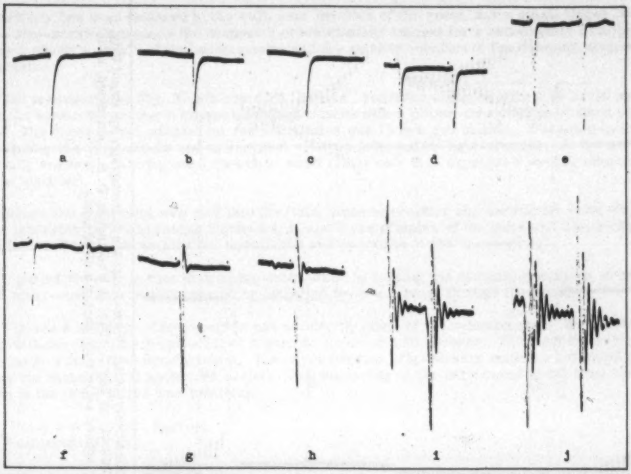


Fig. 4--Damping tests, Wood-Anderson seismometer for Rapid City, South Dakota, on July 9, 1943, at Washington, D. C. [In test (a) magnet at its highest position, that is, in the position for maximum damping; in succeeding tests (b), (c), (d), etc., magnet was lowered by steps of three turns of magnet adjusting-screw; in last test (j) magnet was in its lowest position. A damping ratio of 15 or 20 to 1 is desirable, that is, it should be slightly less than (f) and somewhat more than (g). In this case the free period of the system was about 6 seconds.]

stallation. The school at that time was planning the construction of a new building and wished to make provisions for the future installation of a seismograph.

About three years ago the building was completed and early in 1943 Professor TULLIS was ready to obtain instruments for the proposed station. At that time, however, it was impossible to obtain new instruments of any description. California Institute of Technology and the United States Coast and Geodetic Survey between them had sufficient equipment to lend the South Dakota School of Mines to establish one component.

The seismometer loaned by the California Institute of Technology was a standard Wood-Anderson instrument. The loan of a recorder, pendulum-clock, and miscellaneous accessories to the School by the United States Coast and Geodetic Survey was approved by the Secretary of Commerce after the college authorities had agreed to make available the records for the work of the Survey.

The seismometer was rebuilt and provided with a flat-vane suspension 1 by 8 by 25 mm. The suspension-wire is of tungsten attached along one edge of the vane. The suspension was provided with a plano-parallel front-surface mirror, and a second reflection-mirror to increase the sensitivity. A plano-convex lens of one-meter focal length was provided to focus the spot. The instrument was placed in operation with a static magnification of about 725:1. In order to provide smooth continuous adjustment of the damping magnet the magnet-adjusting screw was changed slightly, as were the pole-pieces. A plano-convex sensitivity mirror was installed on the forward foot-screw. The focal length of this lens was so chosen as to focus the spot on the same recording drum as the regular spot. Figure 1 shows the seismometer with the covers removed.

A rather novel innovation was installed on this instrument to deflect the vane for damping-tests. A small nozzle was inserted through the back of the seismometer-case and connected by a flexible rubber tube to a standard medicine-dropper. The observer may stand across the room and by a slight measured pressure on the rubber bulb of the dropper can deflect the vane a given amount.

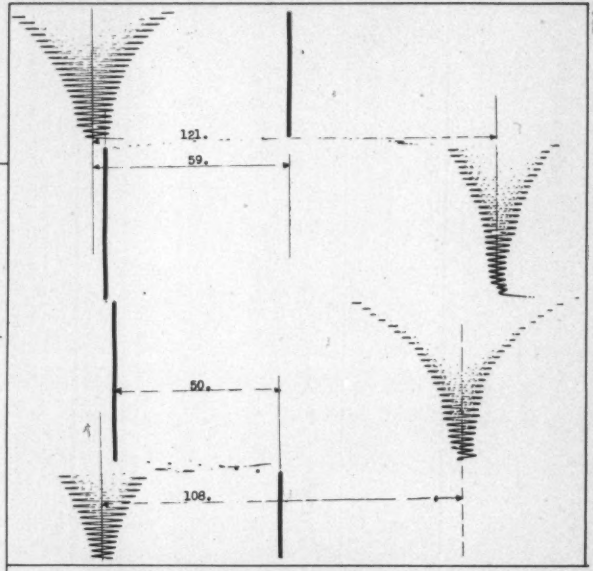
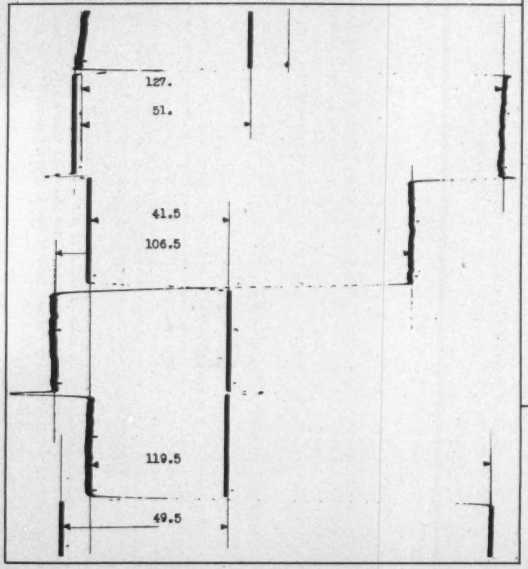


Fig. 5--Sensitivity-tests, Wood-Anderson seismograph for Rapid City, South Dakota, on July 7, 1943, at Washington, D. C.; undamped, as in Fig. 4; second reflection; period 6.60 seconds

Fig. 6--Sensitivity-tests, Wood-Anderson seismograph for Rapid City, South Dakota, on July 7, 1943, at Washington, D. C.; damped pendulum; tests followed Fig. 5 immediately; second reflection; period 6.60 seconds



The dropper has been fastened to the wall, near the door of the room, and a small hinged lever with a stop-screw depresses the dropper a predetermined amount for a satisfactory damping-test. Figure 2 shows a sketch of the seismometer and the relative location of the damping-magnet, vane, and nozzle.

The recorder (see Fig. 3) is a standard "Miller" recorder equipped with a 60-cycle synchronous motor developing a torque of 75 inch-ounces with a power-consumption of about eight watts. The paper-speed adopted for the installation was 15 mm per minute. The drum is capable of operating two components and is provided with two independent light-sources. At the present time only one lamp is being used, though at some future date it is expected a second component will be installed.

Before the equipment was sent into the field, some interesting and instructive tests were made in the laboratory. The following Figures 4, 5, and 6 are samples of the tests and illustrations which were included in the directions for installation and operation of the seismograph.

Figure 4 shows a series of damping-tests made by raising the damping-magnet in steps of three turns--the vane in all cases being deflected by an air-blast through the nozzle.

Figures 5 and 6 are decay-curves and sensitivity-tests of the seismometer. Both tests were made with the instrument operating at a natural period of 6.56 seconds. The first tests (Fig. 5) were made with an undamped system. The second series (Fig. 6) were made on a damped system having the same natural undamped period. The sensitivity of the instrument to tilt from the tests shown in the two Figures was identical.

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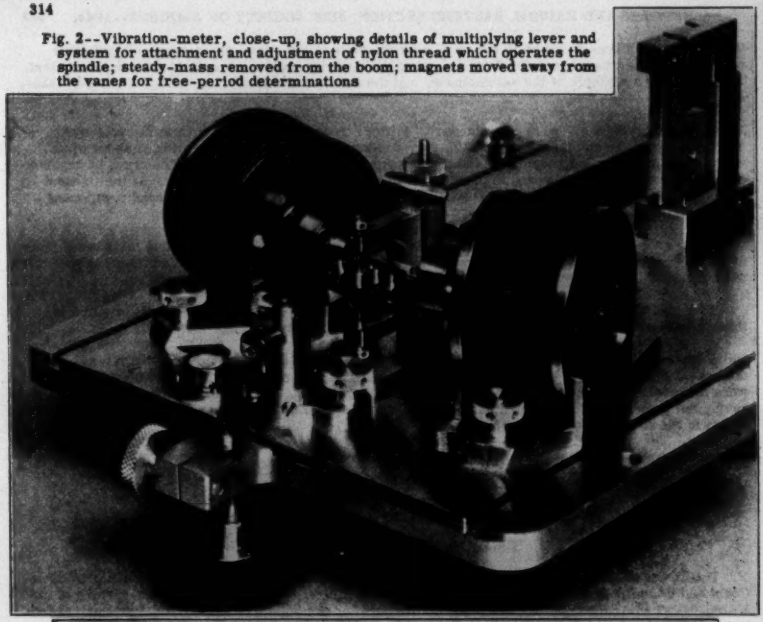
A GENERAL-PURPOSE VIBRATION-METER

Frank Neumann and H. E. McComb

Due to the ever-increasing demand for vibration-observations of many kinds, the United States Coast and Geodetic Survey has undertaken the construction of a number of vibration-meters of the NEUMANN-LABARRE type. In designing the instrument our objective has been the production of a light, compact unit which would at the same time be sufficiently rugged for general field-use. The

Fig. 1--Vibration-meter with large mass mounted on the boom; damping magnets in position for critical damping; cover, with optical glass windows; accessories for making adjustments

Fig. 2--Vibration-meter, close-up, showing details of multiplying lever and system for attachment and adjustment of nylon thread which operates the spindle; steady-mass removed from the boom; magnets moved away from the vanes for free-period determinations



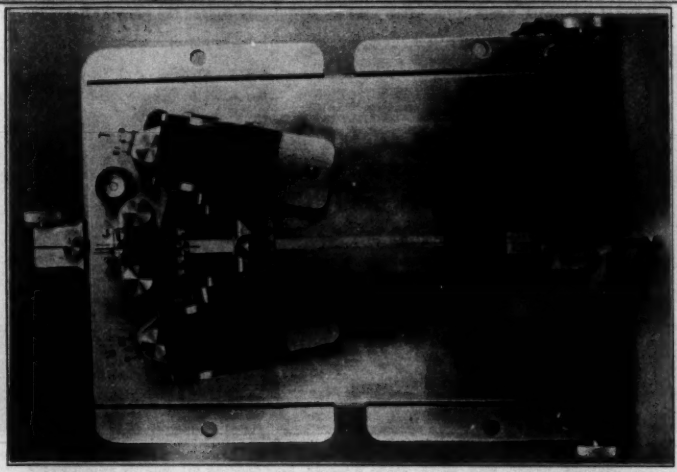


Fig. 3--Plan-view of vibration-meter showing smaller steady-mass in position for maximum magnification for short periods

instrument embodies all of the features of the older models, which experience has shown are reliable and practicable, and, in addition, many new features have been added.

The instrument (see Figs. 1, 2, and 3) consists essentially of a short boom supported by Cardan hinges (under tension) and carrying a heavy mass which may be adjusted to any position along the boom in order to secure the pendulum-length desired. The outer end of the boom terminates in a three-pronged fork with simple clamping-devices so arranged that a nylon thread (for operating the spindle) may be easily installed and the tension adjusted. The thread passes once around a spindle having jeweled bearings. The spindle carries a plano-convex mirror for use in optical registration. The tension of the thread is easily adjusted by hanging a small weight over that part of the thread which lies between two adjacent prongs of the fork, after which the middle clamp is tightened. A right-angle prism mounted directly in front of the mirror is useful in directing the reflected light at right-angles to the boom horizontally or vertically.

The boom is provided with two steady masses of different sizes. These masses are adjustable continuously along the boom, thus providing a wider range of static magnification without the necessity of altering the diameter of the spindle.

Damping is magnetic and is accomplished by means of two cylindrical copper vanes attached on either side of the boom and adjusted so that each is concentric with the axis of a cylindrical damping-magnet. The pole-piece of each damping-magnet is so attached that a radial field is produced in the air-gap in which the damping-vane operates. The vane is so attached that it may be easily and quickly centered and clamped in the air-gap by means of a template. Each magnet (Alnico II) is mounted on an arm which is pivoted about a center directly below the Cardan hinges. Thus the magnets and the vanes swing about the same center and there is no danger of fouling of the vanes in the air-gaps in any position. This makes it possible to adjust the damping-magnets relative to the vanes so that any degree of damping may be obtained. The magnets may be moved outward to the extreme limit for determination of the free-period of the pendulum.

The instrument is provided with a cover with optical-glass windows in order to protect it against air-currents.

Preliminary observations indicate that the instrument may be adjusted to natural periods ranging from 0.85 second to 6.0 seconds, giving static magnifications ranging from 11,500 down to 3,000, the highest magnification being associated with the shortest period.

It is believed that this instrument will serve a very useful purpose, not only in connection with studies of ground-vibrations and vibrations in engineering structures, but in the recording of local shocks, the preliminary waves of distant earthquakes, and microseisms.

U. S. Coast and Geodetic Survey,
Washington, D. C.

THE MEXICAN EARTHQUAKES OF APRIL 15, 1941, AND FEBRUARY 22, 1943

Mary P. Collins and L. Don Leet

(Abstract)

Strong earthquakes were felt in several States of Mexico on April 15, 1941, and February 22, 1943. The shock of 1941 is believed to have been accompanied by an eruption of the Volcano Colima and the shock of 1943 followed the first eruption of Parícutin.

Records of these two earthquakes were loaned to the Harvard Seismograph Station by most of the seismograph-stations of the Western Hemisphere, to the directors of which the writers wish to extend their thanks. Epicenters were located by the modified station-pair method at 19° 04′ north latitude and 103° 06′ west longitude for the earthquake of 1941 and at 17° 55′ north latitude and 101° 05′ west longitude for the shock of 1943. The epicenter of 1941 is approximately 70 km southeast of Colima Volcano, while the shock of 1943 apparently centered 210 km southeast of the new Parícutin. There is some evidence that the depths are slightly greater than normal--about 50 km for the shock of 1943, as deep as 100 km in 1941.

The distribution of initial condensations and dilatations from the earthquake of 1941 falls into

a quadrantal pattern similar to that reported in California. Motion here, however, appears to be in the opposite direction to that observed in California. Initial motion from the earthquake of 1943 seems to be compression at all stations.

The travel-times of the longitudinal waves from these shocks are best described by a series of straight lines with intersections near 16°, 25°, and 45°. Travel-times for shear-waves do not present such a simple picture. Unusual difficulty was experienced with the shear-waves from the shock of 1943, which were recorded late over a considerable range of distance.

A full report of the study will be submitted to the Bulletin of the Seismological Society of America for publication.

Harvard University,
Cambridge, Massachusetts

SOME VOLCANOLOGICAL AND SEISMOLOGICAL CONCLUSIONS REGARDING MEXICO AND CENTRAL AMERICA

Pedro C. Sánchez

Referring to the interesting article of Dr. WILLIAM H. HOBBS [New volcanoes and a new mountain range, Science, April 14, 1944], who makes some comments on new volcanoes and refers besides to the volcanoes of Central America and Mexico, I should state that in my conception these last belong to a region which from the geographical point of view should be called Centro America as I have demonstrated in various of my works but principally in one entitled "Geographical importance of the Volcanic Axis" that Centro America begins at the Cordillera called the Volcanic Axis and practically extends from parallel 19° to the depression of the Atrato River (in Colombia). The term "Centro America" will be used for the area that is defined.

In these volcanoes I distinguish three periods: In the first case the most intense, of explosive character, corresponds to the volcanoes which occupy the crests of the highest mountains; then comes that of medium intensity whose volcanic outlets occupy the flanks; and finally that of least intensity, or decadence, in which the volcanic chimneys appear in the valleys.

All the Centro-American volcanoes are aligned in straight lines known as volcanic axes. That of Mexico has an east-west direction with an extension of more than 900 km and the eruptions have confirmed this direction which is that of the tectonic thrust characteristic of Centro America; then comes that of Guatemala and El Salvador with the direction southeast-northwest, which begins at the volcano of Tocana near the Mexican Frontier and ends at Conchagua at the Gulf of Fonseca; and finally the Nicaraguan, which begins at Cosiguina near the Gulf of Fonseca and ends at Chiriquí with a southeast-northwest direction to meet the Archaean mountain chain of Veraguas, which continues to Panama.

If the number and energy of the active volcanoes of the present time are compared with that of the Tertiary, it is realized that the existing activity is only the remnant and final manifestation of the volcanism of the Miocene--and by this its decadence is manifested.

But to what is this decadence due? Is this a transient phenomenon, or can the activity be intensified in the future?

To the geologist and volcanologist this indicates a diminution of the interior magma in quantity due to crystallization, but in this case a recrudescence would appear to be almost impossible, since the crystallization would increase rather than diminish with time; and on the other hand the diminution of the magma is in contrast with the volume of the mass of lava scattered on the Earth's surface, which, taking into account the dimensions of the Earth and the thickness of the more or less viscous fluid of the magma, can not be less than 40 to 60 km.

All the active volcanoes of Centro America are in the last period of activity and all appear in the valleys, as, for example, the volcano of San Salvador which had an eruption in 1917 and when I visited it in 1936 it already was without fumaroles. The case is the same with Parícutin in Mexico, the most youthful of the volcanoes of Centro America; since it has had scarcely more than a year of existence and gave out very little lava, and though it is still continuing, it is in its decadence since it is mainly throwing out vapor--that is to say, that it has passed to a fumarolic state of weak intensity.

A well-established fact regarding these volcanoes is that the eruptions occur from east to west in such a way that the active volcano is nearest to the Pacific. Perhaps this is due, as OTTO MARIA REIS says, to the centrifugal force resulting from the Earth's rotation since the ascending masses of lava can not move to the east because of the Earth's rotation with the same velocity as the surrounding masses free from the invasion of the lava; hence a retarding of the movement and a pressure toward the west, which drives the ascending magma in this direction and possibly because of the increase in kinetic energy through the increase of the mass and of the velocity, should cause a peripheral movement which would produce tangential forces in the Earth's crust.

Volcanic formations are very numerous in Mexico, but it can be said that the active volcanoes are quite limited in number and very few of them have given signs of activity in historic times; and their eruptions, with the exception of those of Colima, Jorullo, and Ceboruco, have been always of an explosive character--that is to say, they have not emitted a great quantity of lava but principally detritic material, ashes, and abundant emission of gases so that it can be said that their activity is of a fumarolic character.

The eruptions of Popocatépetl, of which there is information, have taken place in the years of 1519, 1539, 1664, 1697, 1720, 1920, and 1921. As is seen, from 1720 to 1920 there is a period of 200 years of repose and the eruption in the latter year was preceded by a strong earthquake whose focus was situated in the volcano.

Of Colima, the first scientific information was due to the French explorers DOLLFUS and MONTSERRAT and was of March, 1866. In 1869 there began a new period of eruptive paroxysm accompanied by strong emanations of vapor and subterranean detonations. Then comes a period of relative calm until 1872 and 1873 in which eruptions were renewed and lava issued from the craters. In 1885 there began a period of great activity, the lava issuing from the principal crater and from the secondary one formed in 1869. In January, 1913, the volcano entered a period of paroxysmal eruption, and since then there has been only fumarolic action of little importance.

Jorullo appeared in 1759; its geological interest is great since it belongs to a historical period relatively recent, but its activity lasted only a few years and in 1906 it had only small fumaroles.

The Ceboruco gave signs of life in 1870, after various earthquakes and intense subterranean noises, and its activity lasted until 1875; since then there have been only very weak fumaroles.

There follows then a great period of calm in the Mexican volcanoes interrupted by the appearance of Paricutin in February, 1943. Its eruptions are very similar to those of Jorullo with little lava and great quantity of detritic material and fumaroles. In this year (1944) its activity has diminished greatly with lava at times issuing from an open fissure on the flank of the crater and with a continuing fumarolic state of decreasing activity. It is possible that this state may last several years.

It can be said then that in Mexico the volcanic activity is in complete decadence.

The situation is similar in Guatemala and in El Salvador where the active Volcano Izalco, which appeared in 1770 almost contemporaneously with Jorullo, is nearly extinct.

The volcanoes of Costa Rica have not given signs of activity in historical times.

The most notable volcano of Centro America is Coseguina near that part of the Gulf of Fonseca which is nearest to Nicaragua. There was an eruption on January 20, 1835, which threw out ashes and lapilli during 43 consecutive hours affecting a surface of 4,000 square km and the volume of the eruption reached 50 cubic km. At 40-km distance the ground was covered with a thickness of ashes and pumice to the depth of five meters and the volcano was reduced almost to a half since its altitude of 2,000 meters was reduced to 1,169 meters.

Almost all the volcanoes of Chile are inactive.

In Ecuador (South America), Cotopaxi has quite frequent eruptions. The most important took place on June 26, 1877. Sangay is famous as the most destructive volcano of the Earth. Its activity never ceases. WISSE AND GARCIA MORENO have counted 267 explosions an hour of varying intensity with ejections of ashes and lava.

Is the recrudescence possible in the future? And what would be its cause?

According to geology, volcanic phenomena are not exclusively of a definite geological period but with distinct intensities appear in many of these periods precisely at the time of great changes and terrestrial disturbances.

But the fact is that the seismic and volcanic phenomena, which without the least doubt respond to the reactions of the internal fluid, are as yet without satisfactory explanation.

Since the theory of isostasy has been confirmed, new light has been thrown on these so interesting phenomena. The places in which they have occurred are characterized by negative anomalies of gravity, as is noted in the conference of the International Union of Geodesy and Geophysics which took place in Stockholm in 1930.

My work on Centra America confirmed my first observations resulting from studies in Mexico, and without any doubt the greater or lesser importance of isostatic lack of equilibrium, which provokes a movement of variable intensity in the internal magma, is the cause of such phenomena.

In tracing the isoanomalies in Centro America, there emerge two important facts: First, that in the volcanic axes the anomaly is zero; and second, that the absolute value indicates the degree of lack of equilibrium, which increases with the numerical value of the anomaly. This observation is due to gravity expeditions of the United States Navy in the Antilles and Caribbean.

[Note: The original manuscript in Spanish was translated by N. H. Heck for publication in these Transactions.]

Pan-American Institute of Geography and History,
Mexico, D.F., Mexico

COMMENTS

N. H. HECK (U. S. Coast and Geodetic Survey, Washington, D. C.)--In the course of translation of this article, it was evident that SANCHEZ is not in accord with HOBBS' interpretation in his article in Science [see Fig. 1, p. 277], but he does not expressly state this. The acceptance of the conception of geological Central America extending from latitude 19° north to Colombia does not fit in with HOBBS' rising ranges. SANCHEZ takes the view that the volcanic activity of both North and South America has greatly decreased since the Miocene and does not consider the "new" volcanoes as renewal of orogenic activity. He makes the point that volcanoes rising from a valley-floor are minor short-lived phenomena. He considers that Parícutin and Jorullo represent the end-process of dying out of volcanic activity of the volcanic axis from east to west, so that the two volcanoes belong to this belt and not to a northwest-southeast structure.

From the viewpoint of a non-volcanologist it seems to me that, in view of the important volcanic activity in parts of Central America and in Ecuador, the picture is not one of early extinction. There has been recrudescence in the past and why should it not happen again, as for example because of radioactivity?

AMERICAN GEOPHYSICAL UNION

TWENTY-FIFTH ANNUAL MEETING

MINUTES GENERAL ASSEMBLIES AND SECTIONS

Washington, D. C.
June 1, 2, and 3, 1944

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TWENTY-FIFTH ANNUAL MEETING (1944)
MINUTES, GENERAL ASSEMBLIES AND SECTIONS

BUSINESS SESSION

The Business Session of the General Assembly of the American Geophysical Union was called to order by Vice-President L. H. ADAMS, in the absence of President W. C. LOWDERMILK, at $13^h\ 35^m$ on Friday, June 2, 1944, in Room 101 of the Hall of Government of George Washington University, Washington, D. C., with a registered attendance of some 70 members (see Appendix A for complete registration of attendance at all sessions of the Twenty-Fifth Annual Meeting).

The minutes of the General Assembly of the Twenty-Fourth Annual Meeting on April 24, 1943, published in the Transactions of 1943 and distributed to all members, were approved as printed.

The annual report of the General Secretary (see Appendix B) was summarized briefly, accepted with thanks, and ordered printed in full in the Transactions of 1944.

Reports of Standing Committees

Chairman Musgrave's report of the Committee on Membership is printed in full in Appendix C.

Chairman Harradon of the Committee on Statutes and By-Laws had nothing to report. The General Secretary reported the almost unanimous adoption by mail vote which closed February 29, 1944, of two additions or modifications of the Statutes, making Article 2, paragraphs (b) and (e) read as follows:

(b) Citizens of the United States of America elected by the Executive Committee of the American Geophysical Union as Members. Citizens of other countries elected as Members by the Executive Committee; these may not be officers of the Union or of its Sections, nor delegates of the Union to international meetings.

(e) Citizens of other countries, who are outstanding in the field of geophysics, elected by the Executive Committee of the American Geophysical Union as Corresponding Members; these shall not pay dues and shall enjoy the privileges of Members except that they may not be officers of the Union or of its Sections nor delegates of the Union at international meetings and may not vote.

Four Corresponding Members have been duly elected since the adoption of the above changes in the Statutes, namely, ALFONSO CONTRERAS ARIAS, HAROLD JEFFREYS, OWEN THOMAS JONES, and PEDRO C. SANCHEZ.

Chairman Swick read the report of the Committee on Budget (see Appendix D). The General Secretary indicated that it would be necessary for the Committee on Budget to prepare a budget for the ensuing year before June 30, 1944.

Chairman Marble of the Committee on Meetings stated that the sessions of the Twenty-Fifth Annual Meeting had been successful and thanked the Secretaries and Presidents of Sections for their part in making the meetings successful. The total registered attendance was 496 (see Appendix A).

Chairman Fleming of the Editorial and Publication Committee stated he had nothing to report other than what was published in the Transactions of 1943 [pp. 314-316] and indicated that if there are any suggestions the Committee would be glad to receive them. He called attention to the fact that the suggestions contained in the report that the Transactions take on the form of a journal to be published bimonthly, that each paper be published by itself, that editorial assistants be appointed for each Section with moderate honorarium, etc., are now important items for the Executive Committee of the Union to decide upon.

Reports of Special Committees

Chairman Field summarized the report of the Committee on Finance (see Appendix E) and asked that the Committee be discharged since its work had been completed by raising $30,000. It was moved, seconded, and carried that the Committee be discharged with thanks and that the greatest appreciation of the Union be expressed for the splendid results obtained by the Committee.

President LOWDERMILK arrived at $14^h\ 00^m$ and took the Chair. He expressed regret that he was late due to an error in the notice he received as to the time the meeting was scheduled to start.

The report of the Special Committee on National Welfare and Related Functions was summarized by Chairman Field (see Appendix F).

Chairman Disney submitted a report for the Special Committee on Cooperation with International Commission for Study of Tidal Waves (see Appendix G).

In the absence of Chairman Hess of the Special Committee on Geophysical and Geological Study of Oceanic Basins, Dr. Thom stated that Dr. Hess is at sea or about to go to sea and that the complete report of the work of the Committee cannot be made available until after the war. (See Appendix H for brief report submitted by mail after the meeting.)

The report of the work of the Special Committee on Geophysical and Geological Study of Continents under the chairmanship of Dr. Thom is given in Appendix I.

New Business

Resolutions--The Committee on Resolutions submitted through Chairman Marble a report recommending the adoption of eight resolutions which, after discussion, were unanimously adopted as follows:

(1) RESOLUTION OF THANKS TO GEORGE WASHINGTON UNIVERSITY

WHEREAS, The authorities of The George Washington University have again made possible a meeting of the American Geophysical Union by their kindly provision of space and facilities, therefore be it

RESOLVED, That the American Geophysical Union heartily thank The George Washington University for its hospitality, and request the General Secretary to express its gratitude to the President of the University.

(2) RESOLUTION ON POSTWAR WORK IN GEOPHYSICS

WHEREAS, The prosecution of the war has been substantially aided by the services of geophysicists and other scientific men, in the planning, development, and operational phases, and

WHEREAS, Much scientific effort that was not deemed immediately helpful to the war-effort has been curtailed, and

WHEREAS, Planning and development work in scientific fields for the postwar era should be undertaken well in advance of entering upon any program, and

WHEREAS, Resolutions (8) on practical programs in all branches of geophysics for the postwar period and (9) on ways and means of providing employment for geophysicists released from the war-effort during the period of transition from war to peace, passed at the Twenty-Fourth Annual Meeting of the American Geophysical Union in April, 1943, pointed a way to action on this subject, therefore be it

RESOLVED, By the American Geophysical Union, in session assembled June 2, 1944, that the two resolutions referred to are hereby endorsed and that plans for the resumption of peace-time programs of research be initiated at an early date and be prosecuted with such vigor as to be in readiness at the termination of hostilities, the demobilization of the armed forces, and the conversion of industry to an economy of peace, but without hindrance to the present war-effort, and be it further

RESOLVED, That the General Secretary of the American Geophysical Union prepare copies of this resolution and the two resolutions referred to and transmit one of each to appropriate executive officers of Federal, State, or other agencies, the staffs of which officers include workers in the geophysical sciences in times of peace.

(3) RESOLUTION OF THANKS TO MAJOR PETER W. RAINIER

WHEREAS, Major Peter W. Rainier favored the Section of Hydrology by presenting an informal communication before them at its meeting on June 2, 1944, therefore be it

RESOLVED, That the American Geophysical Union express its hearty thanks to Major Rainier for consenting to speak to the members of the Union on the notably significant and effective work which he did in providing water-supplies for the British Eighth Army throughout its campaign in 1,500 miles of desert country in North Africa, and be it further

RESOLVED, That the General Secretary be requested to send a copy of this resolution to Major Rainier.

(4) RESOLUTION ON PROPOSED OCEANOGRAPHIC WORK BY THE UNITED STATES HYDROGRAPHIC OFFICE

WHEREAS, The Hydrographic Office of the Navy is empowered by Congress to prepare nautical data for the use of seaiarers, and

WHEREAS, The publications of the Hydrographic Office in the various branches of oceanography have been of great benefit to all seafarers and students of the sea, therefore be it

RESOLVED, That the American Geophysical Union go on record as favoring the establishment at the Hydrographic Office of a permanent unit to specialize in oceanographic work, and be it further

RESOLVED, That the Hydrographic Office be given all help and encouragement to hasten a more complete bathymetric development of the Pacific Ocean, and be it further

RESOLVED, That copies of this resolution be sent to the Secretary of the Navy, to the Chairman of the House Naval Affairs Committee, and to the Chairman of the Senate Naval Affairs Committee.

(5) RESOLUTION ON ESTABLISHMENT OF A GEOPHYSICAL STATION AT THE UNIVERSITY OF ALASKA

WHEREAS, The need for a geophysical station in this country, dedicated to the maintenance of geophysical research concerning the arctic regions, established on a long-term basis, and having functions similar to those carried on by Dr. Carl Störmer and his collaborators in Norway, is recognized, and

WHEREAS, The site at College, Alaska, by virtue of its natural advantages, and in view of the unstinted cooperation of the University of Alaska, was selected as one of the International Polar Year Stations in 1933, as a seismograph-station by the United States Coast and Geodetic Survey in 1936, and as an ionospheric and magnetic observatory by the Department of Terrestrial Magnetism of the Carnegie Institution of Washington in 1941, and

WHEREAS, Geophysical research at College has been productive of results valuable not only as contributions to scientific knowledge, but also of direct military application in the war-emergency, and

WHEREAS, A geophysical station at College would serve the continuing and expanding needs for geophysical information anticipated for the postwar period, and at the same time contribute to the advancement of basic knowledge in the field of geophysics, therefore be it

RESOLVED, That the American Geophysical Union endorse the establishment on a long-term basis of a geophysical station at College, Alaska, to be provided with adequate facilities for the efficient prosecution of auroral, ionospheric, magnetic, and other related researches, and be it further

RESOLVED, That copies of this resolution be sent to the authorities of the University of Alaska, the United States Coast and Geodetic Survey, and the Carnegie Institution of Washington.

(6) RESOLUTION ON INVESTIGATION OF MICROSEISMIC PHENOMENA

WHEREAS, Research in meteorology and allied fields has become of outstanding importance in the war-effort and in the peace-time development of aerial navigation, and

WHEREAS, The full value of microseismic records as an aid in the observation of meteorological phenomena has never been satisfactorily established, even though many valuable contributions have been made, and it is generally agreed that microseisms are of ultimate meteorological origin, and

WHEREAS, There is adequate reason for believing that microseismic observations may have an important application in weather prediction, at least within certain limits, and

WHEREAS, It is recognized that considerable groundwork in collecting factual information must be done before the full usefulness of microseisms as an aid to the science of meteorology can be satisfactorily established, therefore be it

RESOLVED, That the American Geophysical Union express the hope that all agencies and seismological stations which are in a position to make contributions or undertake investigations in the microseismic-meteorological field will make every effort to (a) compile the statistical material necessary for an adequate investigation of microseismic phenomena, and (b) establish the basic facts of the origin and propagation of microseismic waves, and be it further

RESOLVED, That copies of this resolution be sent to the Chief of the United States Weather Bureau, the Director of the United States Coast and Geodetic Survey, and others who may be in a position to make or encourage investigations in this field.

(7) RESOLUTION ON COOPERATION BETWEEN NATIONS OF THE WESTERN HEMISPHERE IN SEISMOLOGY

WHEREAS, The present emergency has created conditions which make it difficult for many seismological stations in Latin America to continue their normal functions, and

WHEREAS, Mutual cooperation in the continuance and further development of such projects in the Western Hemisphere appears necessary if many of the stations are to serve a useful purpose, and

WHEREAS, a central agency, serving as a nucleus for such aid and cooperation, appears essential to successful continuation of these projects, and

WHEREAS, The earthquake-menace in terms of life and property is an ever-present problem to the people of those countries which lie within the destructive earthquake-belts of Latin America, therefore be it

RESOLVED, That the American Geophysical Union express its whole-hearted approval of projects now being undertaken by the Federal Government, notably by the Department of State working in cooperation with the United States Coast and Geodetic Survey, in initiating more active cooperation between the nations of the Western Hemisphere, and in rendering assistance in the maintenance of existing seismological projects, and be it further

RESOLVED, That the American Geophysical Union heartily endorse the action of the Pan-American Institute of Geography and History in offering to serve tentatively as a central agency through which the desired cooperation may be made effective, and be it further

RESOLVED, That copies of this resolution be sent to the Secretary of State, the Secretary of Commerce, the Director of the United States Coast and Geodetic Survey, the President of the Pan-American Institute of Geography and History, and to officials in all of the countries of the Western Hemisphere to which the conditions here outlined apply.

(8) RESOLUTION ON ACCURATE TIME-SERVICE

WHEREAS, There is vital need in all astronomical, geodetic, magnetic, and seismological work for accurate time-service, and

WHEREAS, It is recognized that present war-conditions have introduced complications and difficulties in maintaining routine schedules, therefore be it

RESOLVED, That the American Geophysical Union express its appreciation for all regular and special time-signal services maintained by the United States Naval Observatory, the United States Naval Communications Service, and the National Bureau of Standards, and be it further

RESOLVED, That copies of this resolution be sent to the Secretary of the Navy, the Director of the Naval Communications Service, the Superintendent of the United States Naval Observatory, and the Director of the National Bureau of Standards.

It was moved, seconded, and carried that the Committee on Resolutions be instructed to draw up an appropriate resolution of thanks to the Rockefeller Foundation for their generous cooperation in providing financial aid to the American Geophysical Union.

Elections--Chairman Grover submitted the report of the Committee on Nominations nominating L. H. Adams and Walter H. Bucher for election as President and Vice-President, respectively, of the Union for the three-year period beginning July 1, 1944. There were no other nominations from the floor, and Messrs. Adams and Bucher were unanimously elected.

The Sections reported the election of the following officers for three-year terms beginning July 1, 1944:

Geodesy--W. D. Sutcliffe, President; P. Kissam, Vice-President
Seismology--V. C. Stechschulte, President; Frank Neumann, Vice-President
Meteorology--F. W. Reichelderfer, President; H. R. Byers, Vice-President; H. D. Harradon, Secretary
Terrestrial Magnetism and Electricity--H. F. Johnston, President; Irwin Roman, Vice-President; D. G. Knapp, Secretary
Oceanography--H. U. Sverdrup, President; W. L. Schmitt, Vice-President; L. P. Disney, Secretary
Volcanology--R. E. Fuller, President; Howel Williams, Vice-President; F. G. Wells, Secretary
Hydrology--No elections
Tectonophysics--No elections

The Business Session was moved to Room 200 at $14^h\ 35^m$ because the Section of Meteorology was scheduled to meet in Room 101 for a scientific session.

Reports of Special Committees—Concluded

Chairman Fleming of the Special Committee on Establishment of American Journal of Geophysics recommended that any action to be taken in regard to the establishment of such a journal should be left in the hands of the Executive Committee of the Union, and it was so moved, seconded, and carried.

Chairman McNish of the Auditing Committee reported that the receipts and disbursements for the calendar year 1943 were found essentially correct, that minor modifications have been

carried into the books for 1944, and that a detailed statement has been submitted (see Appendix J). The General Secretary expressed thanks for the report and its correction because of non-entry of two checks in the account book which made last year's balance $239.60 more than actually existed; he explained that the necessary corrections had been made in the books and financial statements.

The report of the Special Committee on Time-Signal Service was read by Chairman McComb (see Appendix K).

Dr. Stetson summarized the report of the Special Committee on Cosmic-Terrestrial Relationships (see Appendix L).

Chairman Colbert of the Special Committee on Award of William Bowie Medal stated that the members of the Committee held no meetings but carried on the function of the Committee through correspondence. Candidates were carefully considered and a selection made as is customary. Announcement of the successful candidate will not be made until the Evening General Session. In connection with the suggestion that a foreign geophysicist be awarded the William Bowie Medal this year, he stated that the Committee believed this was a matter of policy for consideration by the Executive Committee, that it had been referred back to that Committee, and that a mail-ballot by that Committee indicated there should be but one award of the Bowie Medal each year. This report was accepted.

The report of the Special Committee on Precise Surveys and Maps was read by Chairman Swick (see Appendix M).

New Business—Concluded

It was moved and seconded that the question of adherence of the American Geophysical Union to the proposed Council of Geological Organizations be referred to the Executive Committee of the Union for such action as it sees fit. After considerable discussion this motion was passed.

President Lowdermilk called attention to the drive for members, and emphasized that all persons who are eligible to become members should be urged to join at once.

It was moved, seconded, and carried that all of the above reports, that had not been acted upon separately, be accepted and filed.

The meeting adjourned at $15^h\ 24^m$ and was immediately followed by a meeting of the Executive Committee of the Union (see Appendix B).

SESSIONS OF SECTIONS

The minutes of the meetings of the Sections of the American Geophysical Union, June 1, 2, and 3, 1944, are given in Appendices N-a to N-h.

EVENING GENERAL ASSEMBLY

An account of the General Assembly held in Room 101, Hall of Government, George Washington University, at 20^h, June 2, 1944, for the address of the retiring President of the Union and the sixth award of the William Bowie Medal is given on pages 195-215.

J. A. FLEMING, General Secretary,
American Geophysical Union

APPENDIX A--RECORD OF 496 MEMBERS AND GUESTS WHO REGISTERED AT THE TWENTY-FIFTH ANNUAL MEETING

Ackermann, William C.
Adams, John A., Jr.
Adams, L. H.
Adams, Oscar S.
Agy, Vaughn
Ahrens, Thomas P.
Aldredge, R. C.
Ammermen, Dorothea
Anderson, Helen M.
Anderson, J. L.
Anderson, N. G.
Anderson, William L.
Andrews, James F.
Arctowski, H.
Arrow, Kenneth J.
Ashbrook, Joseph

Bailey, D. K.
Bainbridge, W. H.
Baldwin, D. H.
Baldwin, John L.
Balsam, Ella
Bannerman, H. M.
Barrett, Willis C.
Bartsch, Paul
Bay, Helmuth
Beach, Liselotte
Beasley, Ann
Beers, N. R.
Benedict, Paul C.
Benfell, Vincent S.
Bennett, Robert R.
Bennion, V. R.
Bensin, Basil M.
Berdan, Jean M.
Bernard, Merrill
Bernstein, Arthur
Birdsall, John M.
Blake, Archie
Blum, Victor J.
Blythe, John H.
Blythe, R. H., Jr.
Bodle, R. R.
Bodwell, Marion
Bogan, Mrs. Willma W.
Bollay, E.
Bowen, Norman L.
Bowie, John H.
Braaten, Norman F.
Bramhall, E. H.
Brancate, G. N.
Brannock, W. W.
Brashears, M. L.
Breckenridge, Ida S.
Breese, Madame Marie
Brooks, Charles F.
Broughton, John G.
Brown, Carl B.
Brown, Mary E.
Bryan, G. S.
Bryant, Jay C.

Buddington, A. F.
Burke, Margaret F.
Burwell, Edward B., Jr.
Butler, Robert D.
Butterfield, Arthur D.
Byrd, Mrs. Edna T.

Caldwell, Frank E.
Cameron, D. C.
Capello, Jas. J.
Carron, Maxwell K.
Cartwright, G. D.
Chesney, Robert W.
Choate, H. L.
Church, J. E.
Claffey, Mrs. Esther W.
Clapp, Philip F.
Clark, C. O.
Clark, Marjorie A.
Clifford, Charles J.
Clinite, R. G.
Cloos, Ernst
Cohen, Shepard
Colbert, L. O.
Cole, Luke A.
Coleman, Esther A.
Collins, W. D.
Coltrin, Kenneth L.
Conover, Leslie F.
Cook, H. L.
Cooper, Caroline J.
Cornish, John H.
Corwin, Leonard B.
Cotton, Harold A.
Cox, William C.
Crow, Mrs. Eleanor G.
Culnan, Robert N.
Cunney, Geo. A., Jr.

Dale, C. R.
Darling, Frederic W.
Davenport, R. W.
Davids, Norman
Davidson, Norman
Davis, Gordon L.
Davis, Robert M., Jr.
Day, R. L.
DeMallie, Campbell
Derrick, Daniel M.
Dillon, Vincent
Dinaburg, A. G.
Disney, L. P.
Dobrin, Milton B.
Dodson, B. E.
Dorrah, Johnston M.
Doty, L. D.
Dove, W. N.
Drane, Brent S.
Duerksen, J. A.
Duffin, Richard

Eckhardt, E. A.
Eiardi, Anne M.
Eisenlohr, W. S., Jr.
Ellingwood, Cecil F.
Ellis, James R.
Estes, Richard K.

Fahey, Joseph J.
Farnham, Frank C.
Farrell, Mary W.
Feldman, Cyrus
Fiedler, A. G.
Field, Richard M.
Fine, H. J.
Fleischer, Michael
Fleming, John A.
Fletcher, Robert D.
Flint, George M., Jr.
Flynn, Francis J.
Forbush, Scott E.
Forsland, Norma
Forsythe, George E.
Foster, Margaret D.
Fowler, Alvah S.
Fryxell, F. M.
Fuechsel, C. F.

Garner, C. L.
Garrett, Jane R.
Gartlein, C. W.
Gebhardt, Robert E.
Gentry, Robert C.
George, Vernon D.
Gilmore, M. H.
Gilpin, Wm. H.
Gish, O. H.
Glass, Jewell J.
Glock, Waldo S.
Goddard, E. N.
Gold, Harold K.
Goodridge, R. S.
Gordon, Louis
Grabski, Frank
Gracely, F. R.
Grachow, Max
Grange, Mrs. J. C.
Graton, L. C.
Green, J. W.
Griggs, Robert F.
Grover, N. C.
Gruver, Margaret E.
Gunn, Ross

Hain, E. L.
Hamilton, A. R.
Hamilton, Helen C.
Hankins, Lawrence D.
Harker, David H.
Harlan, A. H.
Harned, E. J.
Harradon, H. D.

Harrison, J. O.
Harrison, L. P.
Haworth, Howard F.
Hayes, Albert O.
Haynes, B. C.
Heck, Mrs. Lewis
Hemple, H. W.
Hendrickson, Helena C.
Hendrix, William C.
Hershberger, John
Hess, Irene
Hess, Victor F.
Hewett, Donnel Foster
Higgs, Ralph L.
Hildebrand, Pauline L.
Hobbs, Harold W.
Hoffer, O. S.
Hoffman, Johannes K. P.
Holt, Katherine E.
Hooker, Marjorie
Horton, A. H.
Hough, Floyd W.
Howe, H. H.
Hoylman, H. Wayne
Hoyt, W. G.
Huff, Lyman C.
Hunter, Marvin N.
Hursh, Charles R.
Hurwitz, Louis

Ingerson, Earl
Izzard, Carl F.

Jack, Max C.
Jacob, C. E.
Jacobs, Woodrow C.
Jarvis, Clarence S.
Jenkins, David S.
Jensen, J. C.
Jetter, Karl
Joerg, W. L. G.
Johnson, J. W.
Johnston, H. F.
Jones, T. R.
Jordan, Clarence R.
Joyce, J. W.
Judson, Lewis V.

Kalbfleisch, Albert C.
Kalinske, A. A.
Karrer, S.
Kasel, R. G.
Katz, Harold W.
Keller, Fred
Kennedy, Barbara G.
Keopka, Frances S.
Kesseli, John E.
Keulegan, G. H.
Kirkham, Don
Knapp, David G.
Knoepfel, Margaret F.
Knopf, Adolph
Knopf, Mrs. Adolph
Kohler, J. P.
Kohler, Max A.
Korff, S. A.
Kovach, Edward M.
Krimgold, D. B.
Krumbein, W. C.
Kuehn, Hugo E.

Lackner, Peter R.
Lamar, W. L.
Lambert, Walter D.
Lamson, John L.
Landen, David
Langbein, W. B.
Lange, Isabelle
Laporte, Lucile
Larsen, E. S.
Laure, Linnea
Lay, Edwin T.
Lee, F. W.
Lenz, Arno T.
Liberman, Ena
Lieberman, Harry A.
Light, Phillip
Lindberg, Mrs. Marie L.
Lindley, W. B.
Linehan, Margaret E.
Linskie, Rosella
Little, D. M.
Little, W. S.
Lohr, Edwin W.
Lorimor, Elza G.
Loughlin, G. F.
Lowdermilk, W. C.
Luger, Paul
Lynch, William A.

MacConnell, R. J.
MacDonald, T. H.
Macelwane, James B.
MacKichan, K. A.
Macovsky, Morris S.
Malton, Chas.
Marble, John Putnam
Maris, H. B.
Marmer, H. A.
Marsh, Charlotte A.
Martin, William E.
Mason, Rebecca
Mattice, W. A.
Mayer, Patricia
Mazlen, Henry G.
McCall, A. G.
McCarthy, Daniel V.
McComb, H. E.
McCombs, Charles E.
McCormick, Robert A.
McDonald, W. F.
McGee, Bernard C.
McGuinness, C. L.
McKay, E. C.
McKelvey, V. E.
McKinstry, H. E.
McLendon, Cecil H.
McNiff, Wm. T.
McNish, A. G.
Medina, Guillermo
Meinzer, O. E.
Meinzer, Mrs. O. E.
Melhan, Lorraine
Merriam, Carroll F.
Meyer, Rex R.
Michels, Jean
Mico, Thomas C.
Miller, David H.
Miller, James E.
Miller, LeRoy C.
Miller, Roswell, III
Mills, Richard H.
Milton, Charles
Mitchell, H. C.
Mook, Conrad P.
Moon, George W.
Moorehead, Geo. J.
Morey, H. F.
Morgan, H. R.
Moxham, Robert M.
Mundorff, Maurice J.
Murata, K. J.
Murphy, Leonard M.
Musgrave, G. W.

Nadai, A.
Namias, Jerome
Nelson, O. H.
Nettleton, L. L.
Neuberger, Hans
Neumann, Frank
Nevin, Charles
Newlin, Delmar B.
Nichols, Oscar E.
Norris, Clarence
Norton, Horace W.
Nutting, P. G.
Nye, S. Spencer

O'Connell, Daniel T.
O'Keefe, D. M.
O'Keefe, John A.
Osburn, Raymond C.

Page, Benjamin L.
Parent, Esther L.
Parker, Glenn L.
Parsons, Willard H.
Pate, E. W.
Peltier, Louis C.
Peoples, Joe Webb
Peterson, A. Delbert
Peterson, Barney J.
Phair, George
Pierce, Charles H.
Poling, Austin C.
Pool, H.
Potter, Ursula Yeaworth
Potter, W. D.
Powell, Ralph W.
Pryor, Norma E.

Rabbitt, John C.
Rainier, Peter H.
Ramser, C. E.
Rappleye, Howard S.
Ray, L. L.
Reed, K. L.
Reed, Robert W.
Reichelderfer, F. W.
Rice, Donald A.
Richards, Horace G.
Riesbol, H. S.
Rigby, Malcolm
Roberts, Kenneth L.
Robertson, Florence
Roman, Irwin
Roner, Elizabeth
Rooney, W. J.
Rosenzweig, Oscar
Ross, Clarence S.
Rossby, C.-G.
Rowley, Virginia M.
Rubey, William W.
Rudolph, Muriel C.
Rust, W. M., Jr.

Sarle, Charles F.
Sauer, Jonathan D.
Scharen, H. Leroy
Schereschewsky, P. L.
Schick, Charles O.
Schmidt, Thecla C.
Schmitt, Waldo L.
Schuleen, E. T.
Schwab, John F.
Scott, W. E.
Sears, Mary
Shands, Alexander L.
Shapley, A. H.
Sheridan, Laurence W.
Sherman, K. L.
Shmidl, Leslie E.
Shneiderov, Anatol James
Shofnos, William
Simmons, L. G.
Singewald, Joseph T., Jr.
Siple, Paul A.
Slater, C. S.
Small, James B.
Smith, F. G. Walton
Smith, H. T. U.
Smith, Paul A.
Smith, Robert L.
Smith, Waldo E.
Snyder, Franklin F.
Snyder, Janet
Sollenberger, Lucy
Sollins, Alfred D.
Solomon, Irving
Somers, George B.
Soroka, Mary P.
Speert, Julius L.
Spencer, Richard N.
Steele, Rhea B.
Steiner, W. F.
Stetson, Harlan T.
Stevens, R. E.
Stevlingson, D. J.
Stoiber, Richard E.
Straley, H. W., III
Straley, Mrs. H. W.
Stringfield, V. T.
Sumner, Howard C.
Sutcliffe, Walter D.
Swainson, O. W.
Swartz, J. H.
Sweet, James S.
Swenson, Bennett
Swenson, Frank A.
Swick, C. H.
Swinnerton, Allyn C.

Taylor, Arnold B.
Taylor, Harold A.
Taylor, James H.
Templeton, J. S.
Terry, Jack M.
Thom, W. T., Jr.
Thomas, Margaret S. B.
Thorssen, Alfred H.
Thornthwaite, C. W.
Tibbott, Edward W.
Townsend, Elva H.
Trask, Parker D.
Tuckerman, Bryant
Tuttle, O. F.

Ulrich, Franklin P.

Vacquier, V.
Van Straten, F. W.
Varnes, D. J.
Vestine, E. H.
Vice, Raymond B.

Waddle, Buren A.
Wahrhafty, Clyde
Wait, G. R.
Wallis, W. F.
Walsh, James
Waring, G. A.
Watson, F. G.
Watt, William G.
Weed, Frederick H.
Wells, Francis G.
Wells, H. W.
Wenner, Frank
Wentworth, Eleanor E.
Whitcroft, Thomas H.
White, Donald E.
White, Mrs. Donald E.
Whitten, Charles A.
Whittenberg, C. B.
Wilks, John E.
Williams, Gordon R.
Williams, P.
Willson, Betty May
Wilson, R. M.
Winslow, Allen G.
Winterkorn, Hans F.
Wood, L. E.
Wood, Robert L.
Woolard, Edgar W.
Wrather, W. E.

Zetler, Helen E.
Zies, E. G.
Zietz, Isadore
Zimmer, M. L.
Zoch, Richmond T.

APPENDIX B--REPORT OF GENERAL SECRETARY OF THE AMERICAN GEOPHYSICAL UNION TO THE GENERAL ASSEMBLY, TWENTY-FIFTH ANNUAL MEETING, JUNE 2, 1944

Membership--As of May 27, 1944, the total number of Members was 2,151, a net increase during the year of 253--excellent evidence of the efficiency of our Committee on Membership. Twenty-six of our Members were placed, upon request, on the inactive list, one was reinstated, nine resigned, and nine were dropped because of non-payment of dues during two years. The deaths of 19 Members, since those indicated at the Twenty-Fourth Annual Meeting, were reported as follows:

Jay A. Bonsteel, April 27, 1943
Burton M. Varney, June 4, 1943
Leslie A. Walker, June 29, 1943
Frank Schlesinger, July 12, 1943
W. E. Stodghill, August 1, 1943
G. W. Littlehales, August 12, 1943
E. H. Bowie, August 20, 1943
A. G. McAdie, November 1, 1943
J. W. Howard, January 24, 1944
Paul Bean, January 29, 1944
F. G. Clapp, February 18, 1944
Roy E. Dickerson, February 24, 1944
Frank L. Cooper, February 25, 1944
Benjamin Miller, March 23, 1944
George Steiger, April 18, 1944
Roger C. Wells, April 18, 1944
Theodore B. Parker, April 27, 1944
Salvatore Pagliuca, May 1944
Alexander Breese, May 20, 1944

Besides these, two men (long active Members who had been transferred to the inactive list) died, namely, Charles F. Marvin on June 7, 1943, and Arthur Keith on February 7, 1944.

There are now four Corresponding Members, including Alfonso Contreras Arias (reported in last year's report) and Pedro C. Sánchez of Mexico, and Owen Thomas Jones and Harold Jeffreys of England.

Executive Committee Meetings--The Executive Committee held one meeting on November 20, 1943, with 20 of the Committee attending, and is to hold another immediately following the General Assembly on June 2, 1944. (Note: For purpose of record, the minutes of the meetings of the Executive Committee on June 2 and 29, 1944, are included with this report.) The Committee continued to give special attention to relations of the American Geophysical Union with the International Union of Geodesy and Geophysics, with the International Meteorological Organization, and with our colleagues throughout the Western Hemisphere.

Meetings--A regional joint meeting of the South Pacific Area of the Section of Hydrology, the Western Snow-Conference, and the Pacific Coast Section of the American Society of Agricultural Engineers was held at Berkeley, February 17 and 18, 1944. The manuscripts of papers and reports presented at that meeting were not received until late in May; these will appear as Part I of the Transactions of 1944.

The Twenty-Fifth Annual Meeting of the Union and its Sections was arranged for June 1, 2, and 3, 1944. As for our meeting of last year, we have the privilege of the facilities of the Hall of Government of George Washington University through President Cloyd Heck Marvin. Despite the emergency, the scientific program included 128 contributed papers and progress-reports and the registered attendance was greater than that of the Annual Meeting of 1943. The success of this Meeting--marking one-quarter century of our Union--is due to the excellent and energetic work of the Committee on Meetings under the Chairmanship of John Putnam Marble.

William Bowie Medal--The Special Committee on the Award of the William Bowie Medal has recommended that the sixth award be made to Henry Bryant Bigelow at the General Assembly on the evening of June 2, 1944.

Publications--A revised 72-page list of members and officers as of October 15, 1943, to replace that of February 15, 1942, was prepared. Changes of address have been unusually numerous so that the revised list is already out of date for many addresses. All Members are requested to give prompt advice of changes of address; it is planned to publish a new list early in 1945.

Parts I, II, and III of the Transactions of 1943 total 891 pages (equivalent to 1,300 pages in ordinary printer's format). Part I (332 pages) is devoted to reports and papers at the Twenty-Fourth Annual Meeting at Washington and includes those of the General Assembly and of all Sections except the Section of Hydrology; Part II (454 pages) contains the papers and progress-reports of the Section of Hydrology; Part III (99 + 6 pages) includes those at the joint regional meeting of the Section of Hydrology and the Western Snow-Conference at Corvallis, Oregon, June 16, 1943. The total cost of the Transactions of 1943 was $4,592.41; this covers preparation of master-copy, necessary drafting and redrafting, photographic work, printing, and binding. A stock has been set aside, as usual, for future distribution to our colleagues abroad when conditions permit.

Publication of "Bibliography of Hydrology of the United States of America" for the years 1941 to date had to be postponed. It is hoped that the Section of Hydrology may soon find opportunity and the necessary editorial assistance to prepare the seventh volume in this series for 1941-44.

OFFICERS OF AMERICAN GEOPHYSICAL UNION SINCE ORGANIZATION IN 1919

(The officers of the Union and of its individual Sections until April 28, 1938, were designated as Chairman, Vice-Chairman, and General Secretary (for the whole Union) and Secretary (for Sections); thereafter the designations have been President, Vice-President, General Secretary, and Secretary.)

Section	President	Vice-President	Secretary
	General officers of the Union		
Union	W. Bowie (1920-1922)	L. A. Bauer (1920-1922)	H. O. Wood (1919-1921)
	L. A. Bauer (1922-1924)	A. L. Day (1922-1924)	W. J. Humphreys (1921-1922)
	H. F. Reid (1924-1926)	H. S. Washington (1924-1926)	W. Bowie (1922-1925)
	H. S. Washington (1926-1929)	G. W. Littlehales (1926-1929)	J. A. Fleming (1925-1946)
	W. Bowie (1929-1932)	L. H. Adams (1929-1932)	
	W. J. Humphreys (1932-1935)	A. H. Clark (1932-1935)	
	N. H. Heck (1935-1938)	R. M. Field (1935-1938)	
	R. M. Field (1938-1941)	W. C. Lowdermilk (1938-1941)	
	W. C. Lowdermilk (1941-1944)	L. H. Adams (1941-1944)	
	L. H. Adams (1944-1947)	W. H. Bucher (1944-1947)	
	Officers of the Sections		
(a) Geodesy	W. Bowie (1920-1922)	J. F. Hayford (1920-1922)	H. O. Wood (1920-1922)
	J. F. Hayford (1922-1924)	R. L. Faris (1922-1924)	W. Bowie (1922-1925)
	R. L. Faris (1924-1926)	J. F. Hayford (1924-1925)	W. D. Lambert (1925-1931)
	W. Bowie (1926-1929)	W. Bowie (1925-1926)	C. H. Swick (1931-1937)
		F. E. Wright (1926-1929)	W. D. Sutcliffe (1937-1943)
	W. D. Lambert (1929-1932)	L. J. Briggs (1929-1932)	J. A. Duerksen (1943-1946)
	H. G. Avers (1932-1935)	D. C. Barton (1932-1935)	
	C. L. Garner (1935-1938)	P. H. Underwood (1935-1938)	
	C. H. Swick (1938-1941)	R. M. Wilson (1938-1941)	
	R. M. Wilson (1941-1944)	C. R. Longwell (1941-1944)	
	W. D. Sutcliffe (1944-1947)	P. Kissam (1944-1947)	
(b) Seismology	H. F. Reid (1920-1922)	J. C. Branner (1920-1922)	H. O. Wood (1920-1922)
	W. J. Humphreys (1922-1924)	J. B. Woodworth (1922-1924)	D. L. Hazard (1922-1928)
	J. B. Woodworth (1924-1926)	L. H. Adams (1924-1926)	F. Neumann (1928-1931)
	L. H. Adams (1926-1929)	N. H. Heck (1926-1929)	H. E. McComb (1930-1936)
	N. H. Heck (1929-1932)	F. Wenner (1929-1932)	F. Neumann (1936-1941)

OFFICERS OF AMERICAN GEOPHYSICAL UNION SINCE ORGANIZATION IN 1919--Continued

Section	President	Vice-President	Secretary
	Officers of the Sections — Continued		
(b) Seismology (Concluded)	F. Wenner (1932-1935)	F. W. Lee (1932-1935)	A. Blake (1941-1945)
	F. W. Lee (1935-1938)	J. B. Macelwane (1935-1938)	
	J. B. Macelwane (1938-1941)	H. E. McComb (1938-1941)	
	H. E. McComb (1941-1944)	V. C. Stechschulte (1941-1944)	
	V. C. Stechschulte (1944-1947)	F. Neumann (1944-1947)	
(c) Meteorology	C. F. Marvin (1920-1922)	W. J. Humphreys (1920-1922)	A. J. Henry (1920-1929)
	E. H. Bowie (1922-1924)	R. DeC. Ward (1922-1924)	O. H. Gish (1929-1935)
	C. G. Abbot (1924-1926)	H. H. Kimball (1924-1926)	H. D. Harradon (1935-1947)
	H. H. Kimball (1926-1929)	G. W. Littlehales (1926-1929)	
	G. W. Littlehales (1929-1932)	W. R. Gregg (1929-1932)	
	W. R. Gregg (1932-1935)	C. F. Brooks (1932-1935)	
	C. F. Brooks (1935-1938)	R. H. Weightman (1935-1938)	
	R. H. Weightman (1938-1941)	C. W. Thornthwaite (1938-1941)	
	C. W. Thornthwaite (1941-1944)	C.-G. Rossby (1941-1944)	
	F. W. Reichelderfer (1944-1947)	H. R. Byers (1944-1947)	
(d) Terrestrial Magnetism and Electricity	L. A. Bauer (1920-1922)	W. F. G. Swann (1920-1922)	J. A. Fleming (1920-1929)
	W. F. G. Swann (1922-1924)	L. A. Bauer (1922-1924)	H. W. Fisk (1929-1932)
	L. A. Bauer (1924-1926)	N. H. Heck (1924-1926)	E. O. Hulburt (1932-1938)
	N. H. Heck (1926-1929)	J. H. Dellinger (1926-1929)	J. W. Joyce (1938-1944)
	D. L. Hazard (1929-1932)	L. W. Austin (1929-1932)	D. G. Knapp (1944-1947)
	J. A. Fleming (1932-1935)	S. B. Nicholson (1932-1935)	
	O. H. Gish (1935-1938)	T. H. Johnson (1935-1938)	
	E. O. Hulburt (1938-1941)	E. A. Eckhardt (1938-1941)	
	E. A. Eckhardt (1941-1944)	H. F. Johnston (1941-1944)	
	H. F. Johnston (1944-1947)	Irwin Roman (1944-1947)	
(e) Oceanography	G. W. Littlehales (1920-1922)	A. G. Mayor (1920-1922)	J. T. Watkins (1920)
	J. P. Ault (1922-1924)	G. W. Littlehales (1922-1924)	W. E. Parker (1920-1923)
	N. H. Heck (1924-1926)	W. J. Peters (1924-1926)	G. T. Rude (1923-1926)
	T. W. Vaughan (1926-1928)	G. T. Rude (1926-1928)	A. H. Clark (1926-1929)

OFFICERS OF AMERICAN GEOPHYSICAL UNION SINCE ORGANIZATION IN 1919--Concluded

Section	President	Vice-President	Secretary
	Officers of the Sections — Concluded		
(e) Oceanography (Concluded)	R. L. Faris (1928-1929)	W. J. Peters (1928-1929)	H. A. Marmer (1929-1932)
	(Messrs. Faris and Peters elected at Ninth Annual Meeting to complete terms of officers who resigned because of expected absences from United States during 1929.)		
	A. H. Clark (1929-1932)	H. B. Bigelow (1929-1932)	C. O. Iselin (1932-1935)
	H. A. Marmer (1932-1935)	T. G. Thompson (1932-1935)	P. C. Whitney (1935-1941)
	T. G. Thompson (1935-1938)	C. O. Iselin (1935-1938)	Waldo L. Schmitt (1941-1944)
	C. O. Iselin (1938-1941)	G. F. McEwen (1938-1941)	L. P. Disney (1944-1947)
	P. C. Whitney (1941-1944)	H. U. Sverdrup (1941-1944)	
	H. U. Sverdrup (1944-1947)	Waldo L. Schmitt (1944-1947)	
(f) Volcanology	H. S. Washington (1920-1922)	R. A. Daly (1920-1922)	H. O. Wood (1920-1921)
	L. H. Adams (1922-1924)	T. A. Jaggar, Jr. (1922-1924)	R. B. Sosman (1921-1928)
	T. A. Jaggar, Jr. (1924-1929)	N. L. Bowen (1924-1926)	C. N. Fenner (1928-1932)
		F. E. Wright (1926-1929)	A. H. Koschmann (1932-1935)
	A. L. Day (1929-1932)	R. A. Daly (1929-1932)	E. Callaghan (1935-1938)
	C. N. Fenner (1932-1935)	E. S. Larsen (1932-1935)	J. Gilluly (1938-1940)
	E. T. Allen (1935-1938)	W. S. Burbank (1935-1938)	E. Ingerson (1940-1941)
	E. G. Zies (1938-1941)	A. Knopf (1938-1941)	J. S. Vhay (1941-1944)
	A. F. Buddington (1941-1944)	J. F. Schairer (1941-1944)	F. G. Wells (1944-1947)
	R. E. Fuller (1944-1947)	Howel Williams (1944-1947)	
(x) Geophysical Chemistry	A. L. Day (1920-1922)	F. W. Clarke (1920-1922)	R. B. Sosman (1920-1924)
	H. S. Washington (1922-1924)	W. Cross (1922-1924)	
	(Section was discontinued May 31, 1924, as International Union failed to provide for such a Section.)		
(g) Hydrology (Section organized November 15, 1930)	O. E. Meinzer (1930-1933)	R. E. Horton (1930-1933)	H. N. Eaton (1930-1933)
	C. S. Scofield (1933-1936)	C. H. Lee (1933-1936)	K. H. Beij (1933-1945)
	L. K. Sherman (1936-1939)	J. E. Church (1936-1939)	
	N. C. Grover (1939-1942)	M. P. O'Brien (1939-1942)	
	J. E. Church (1942-1945)	L. G. Straub (1942-1945)	
(h) Tectonophysics (Section organized April 9, 1940)	L. H. Adams (1940-1943)	R. A. Daly (1940-1943)	D. T. Griggs (1940-1943)
	E. Cloos (1943-1946)	L. L. Nettleton (1943-1946)	M. K. Hubbert (1943-1946)

Representation on Divisions of the National Research Council--The Union is now represented on the Division of Foreign Relations of the National Research Council by the following Members: J. E. Church; R. M. Field; J. A. Fleming; N. H. Heck; W. C. Lowdermilk; T. G. Thompson; and P. C. Whitney. (Note: Effective July 1, 1944, W. C. Lowdermilk was replaced by L. H. Adams for the three-year term 1944-47.)

Finances--The report of the Committee on Audit for the calendar year 1943 is given in full in Appendix J. That Appendix includes a statement of receipts and expenditures from January 1 to December 31, 1943. As in previous years, the National Research Council assisted the Union by a grant of $400 for the fiscal year ending June 30, 1944, and has made a grant of like amount for the fiscal year ending June 30, 1945.

The year has been marked by the realization of the Union's long-planned Special Fund to secure for a three-year period from July 1, 1944, a total of $30,000 (in addition to annual dues from Members) to provide for full-time services of a paid Executive Secretary and clerical assistance consonant with the forwarding of the Union's activities. The success of this undertaking was largely due to the efforts of our Special Committee on Finance of which R. M. Field was Chairman and in which he was most ably seconded by G. W. Musgrave as Vice-Chairman; each Section was represented by Sub-Committees on Finance as noted in the report of the Special Committee (see Appendix E).

Statutes and By-Laws--Two changes in the Statutes and By-Laws were made by a mail ballot which closed February 29, 1944. Seven hundred and ninety-eight ballots were received and the vote was overwhelmingly affirmative for revisions of paragraphs (b) and (e) of Article II on Membership as follows:

(b) Citizens of the United States of America elected by the Executive Committee of the American Geophysical Union as Members. Citizens of other countries elected as Members by the Executive Committee; these may not be officers of the Union or of its Sections, nor delegates of the Union to international meetings.

(e) Citizens of other countries, who are outstanding in the field of geophysics, elected by the Executive Committee of the American Geophysical Union as Corresponding Members; these shall not pay dues and shall enjoy the privileges of Members except that they may not be officers of the Union or of its Sections nor delegates of the Union at international meetings and may not vote.

Miscellaneous--A Special Committee on Precise Surveys and Maps was appointed in accordance with the resolution passed at the Annual Meeting of 1943; its first report is given as Appendix M.

Because of frequent requests for names of the officers of the Union since organization in 1919, the General Secretary prepared a list as given on pages 330, 331, and 332, in which are included also those officers elected during the Twenty-Fifth Annual Meeting.

International Union of Geodesy and Geophysics--Complete functions of the International Union of Geodesy and Geophysics could not be maintained. The officers of the International Union in Great Britain and the United States, however, were able to continue some of them, thus paving the way for postwar resumption of international collaboration. [In this connection, see Trans. Amer. Geophys. Union, Part I, pp. 294-295, 1943.]

The quota of $3,920.40 for adherence of the United States to the International Union for the calendar year 1943 was received June 14, 1944. The balance on June 2, 1944, deposited with the Riggs National Bank, was $18,093.72.

The International Commission on Continental and Oceanic Structure made excellent progress during the past year under the effective chairmanship of R. M. Field.

Another successful year has been added in the history of our Union and in the Union's service to geophysical progress. The realization of the Special Fund and the advances that will result therefrom are certain to increase the sphere of usefulness of our body both nationally and internationally.

J. A. FLEMING, General Secretary
American Geophysical Union

MEETINGS OF EXECUTIVE COMMITTEE, JUNE 2 AND 29, 1944

Minutes of June 2, 1944

The meeting was called to order at $15^h\ 27^m$ by President Lowdermilk in Room 200 of the Hall of Government, George Washington University.

Present--The following persons were present: L. H. Adams, A. Blake, A. F. Buddington, J. E. Church, E. Cloos, L. O. Colbert, J. A. Duerksen, R. M. Field, J. A. Fleming, H. D. Harradon, W. G. Hoyt, H. F. Johnston, W. D. Lambert, W. C. Lowdermilk, J. P. Marble, H. E. McComb, A. G. McNish, G. W. Musgrave, L. L. Nettleton, J. W. Peoples, W. W. Rubey, W. L. Schmitt, H. T. Stetson, C. H. Swick, W. T. Thom, Jr., C. W. Thornthwaite, H. M. Wilson; Messrs. L. P. Eisenhart, N. H. Heck, M. K. Hubbert, C. R. Longwell, V. C. Stechschulte, H. U. Sverdrup, and T. G. Thompson were excused because of absence from the city or previous engagements.

Approval of Minutes--Minutes of previous meeting of November 20, 1943, were distributed by mail; one correction has been indicated, namely, the financial statement requires modification because two checks were not entered in the account book. The minutes as circulated were approved after correction as stated above.

General Secretary's Report

Personnel--Mrs. J. C. Grange and Mrs. E. M. Lanigan (part time) were continued as assistant secretary and clerk, respectively.

Financial Report--On May 27, 1944, the total cash balance of all funds deposited with the Riggs National Bank, Chevy Chase Branch, was $11,743.43, including the following accounts: American Geophysical Union, $5,338.56; Special Fund, $4,705.50; Bowie Medal Fund, $185.60; Washington Assembly, $1,513.77.

Upon consideration of the recapitulation of funds of the Union it was moved and carried that $3,500 be transferred from the accumulated balance to the Special Fund.

Membership--The total membership in accordance with the list of October 15, 1943, was on that date 2,075. Since the meeting of November 20, 1943, new Members and Associate Members have been elected as per Tables 1 and 2.

Table 1--Members elected since 24th Annual Meeting in April, 1943

1943		1943		1944		Summary	
May 1	22	Aug. 6	17	Jan. 19	12	Total on Apr. 23,	
28	13	20	9	Feb. 1	12	1943.	1898
June 2	40	Sep. 28	13	28	19	Total on May 27,	
21	25	Nov. 23	24	Apr. 5	19	1944.	2151
July 1	36	Dec. 30	9	May 11	11	Net increase. .	253
17	11			27	14		
				Total	306		

Table 2--Comparison of affiliations with Sections, May 31, 1944, and October 15, 1943

Section	Affiliations		Section	Affiliations	
	May 31, 1944	Oct. 15, 1943		May 31, 1944	Oct. 15, 1943
a	389	371	f	288	269
b	447	427	g	1272	1227
c	775	753	h	447	416
d	391	380	Totals	4382	4211
e	373	368	Members	2151	2075

In addition to those reported November 20, 1943, the following Members have died: Burton M. Varney, June 4, 1943; J. W. Howard, January 24, 1944; Paul Bean, January 29, 1944; F. G. Clapp, February 18, 1944; Roy E. Dickerson, February 24, 1944; Frank L. Cooper, February 25, 1944; Benjamin Miller, March 23, 1944; George Steiger, April 18, 1944; Roger C. Wells, April 18, 1944; Theodore B. Parker, April 27, 1944; Salvatore Pagliuca, May 19, 1944 (date notice received); Alexander Breese, May 20, 1944. Arthur Keith, who was on the inactive list, died February 7, 1944.

Nine Members were dropped December 31, 1943, for non-payment of dues during two years. Thirteen Members were placed on the inactive list upon request. Eight Members resigned. Even with these losses by death, dropping, transfer to inactive list, and resignations, the total number of Members May 27, 1944, is 2151; this is a net increase of 76 since November 20, 1943--thanks to the good work of our Committee on Membership.

Except for ten Members in enemy countries whose payments for dues have been postponed by action of the Executive Committee, there are 35 Members who are delinquent in dues for the two years 1942 and 1943, in accordance with the attached list, 47 Members who have not yet paid their dues for 1943 and 1944, and 500 who have not yet paid their dues for 1944. (Note: The list referred to is not reprinted here.)

Upon the recommendation of the Committee on Membership and action unanimously approved in correspondence vote by the Executive Committee, Harold Jeffreys and Owen Thomas Jones of England were duly elected Corresponding Members. Including Alfonso Contreras Arias and Pedro C. Sánchez of Mexico, the Union now has four Corresponding Members.

Twenty-Fifth Annual Meeting--The Twenty-Fifth Annual Meeting, during June 1, 2, and 3, 1944, at the George Washington University, included 128 scientific papers and progress-reports, as listed in the attached program and supplementary program. (Note: The programs are not reprinted here.) The Chairman of the Committee on Meetings is J. Putnam Marble.

Regional Meeting--Authority for publication in the Transactions of the manuscripts for the Berkeley Regional Meeting of February 18 and 19, 1944, to include papers and discussions at the joint meeting with the Western Snow-Conference, was authorized.

National Research Council--The National Research Council advised it had made an allotment to the Union of $400 for the fiscal year July 1, 1944, to June 30, 1945.

Reappointments or new appointments are to be made to National Research Council for representatives from American Geophysical Union on its Division of Foreign Relations to succeed R. M. Field, N. H. Heck, and W. C. Lowdermilk. (Note: The first two were reappointed and the last was replaced by his successor as President of the American Geophysical Union, L. H. Adams, each for three-year term from July 1, 1944.

The General Secretary reported on work of the Union at the April 1944 meeting of the Division of Foreign Relations.

Publications--Part II (454 pages) of the Transactions of 1943 was finally received in March, 1944, and promptly distributed, as were also the reprints ordered from that Part.

International Union of Geodesy and Geophysics--Dues of $3,920.40 for the calendar year 1942 for adherence of the United States in the International Union of Geodesy and Geophysics were received and deposited February 3, 1944, with the Riggs National Bank of Washington in the name of the International Union of Geodesy and Geophysics by Jno. A. Fleming, Vice-President; balance on deposit May 27, 1944, was $14,173.23. The officers in the United States of the International Union judge it wise to hold intact in the account all payments received for calendar years beginning with that for 1941 because the Washington Assembly agreed that payments would discontinue after 1940. The Committee suggested that Vice-President Fleming discuss with National Research Council investing dues from 1941 in United States War Bonds (series G).

Correspondence was maintained with General Secretary Winterbotham of the International Union, in particular as regards postwar reorganization and financial matters. (There was discussion of various questions raised by General Secretary Winterbotham as regards "Emergency" President, Vice-Presidents, and other officers; Secretary Winterbotham has suggested W. D. Lambert for Geodesy, J. E. Richey for Volcanology, R. Stonely as acting Vice-President for Seismology, and would like suggestions for Emergency President for Hydrology.) International funds were provided by General Secretary Winterbotham for International latitude work at Naples by Carnera and for the Seismological Bulletin in England.

A letter dated November 23, 1943, from the office of the Norwegian Embassy at Washington and signed for the Ambassador by L. Jorstad, Counselor of Embassy, states that Dr. B. Helland-Hansen has been authorized by the Norwegian Government to invite the International Union of Geodesy and Geophysics to hold its proposed 1942 triennial meeting in Norway and that the Ministry considers the invitation to be still in force and regards it as a great honor for Norway to be

host for the next meeting of the Union, in which so many Norwegian scientists have taken active part.

Miscellaneous--The National Roster of Scientific and Specialized Personnel has made up a special description of the Profession of Geophysics for the Bureau of Placement of the War Manpower Commission.

The General Secretary was instructed to arrange for deposit of originals of exhibit maps in Washington because (a) the D and W Blueprint Company feels its expense for storage is not warranted, and (b) to prevent loss of originals or future misplacement.

Authority was given G. P. Woollard to use the Humble Oil and Refining Company's truck and gravity meter on loan to the Union for some special work in the St. Lawrence area, New Brunswick, Canada.

Actions on General Secretary's Report--It was agreed that, under existing emergency conditions, more time should be given the Members who are delinquent for 1942 and 1943 before dropping them, particularly as many are in the armed forces. The General Secretary's report was ordered accepted and filed.

Reports of Standing and Special Committees

These reports, which had already been submitted at the Business Session of the Union held just prior to the meeting of the Executive Committee, were ordered accepted for publication in the Union's Transactions of 1944.

It was noted that the Western Snow-Conference had made a contribution of $100 to the Special Fund. There was also contributed by Theodore Wentworth the sum of $500 in memory of his father, Hugo O. Wentworth, who had attended the Edinburgh Assembly of the International Union of Geodesy and Geophysics in 1936.

Business of Sections

President Lowdermilk then called for reports, comments, or suggestions relating to activities of Sections from the Presidents of Sections, or their representatives.

Geodesy, Seismology, Meteorology, Terrestrial Magnetism and Electricity, Oceanography--No reports.

Volcanology--Reference was made to a very interesting letter dated December 31, 1943, received by President Lowdermilk from Dr. Buddington regarding volcanology and possibilities of future research-work.

Hydrology--The General Secretary advised that the Executive Committee of the Section of Hydrology desired to establish (a) a system of honors and/or awards for meritorious papers in hydrology, and (b) intersociety affiliations and designation of Union representatives. It was moved, seconded, and carried that the Executive Committee of the Union authorize a Section, when it so desires and informs the Executive Committee of the Union of such action, to make a citation for a meritorious paper within the Section by the Executive Committee of theSSection.

It was moved, seconded, and carried that the Section of Hydrology and any other Section of the Union that wishes may arrange committees of amity with other closely related organizations with whom it can work in greater sympathy and understanding and sometimes on common programs, this to be called an intersociety relationship. A motion was also made, seconded, and passed that the Executive Committee of the Union commends to the Sections the carrying out of cooperative activities with other scientific organizations in their fields.

New Business

Special Committee on Future Policy of the Union--With reference to the new financial set-up by reason of the completion of the Special Fund of $10,000 plus financial aid of $20,000 for three years from July 1, 1944, to June 30, 1947, from the Rockefeller Foundation, the Executive Committee discussed (a) responsibility of paid Executive Secretary, (b) elected General Secretary, (c) relations of paid Executive Secretary to President, Vice-President, and General Secretary, and to Executive Committee, (d) provision of quarters, (e) compensation for responsible Co-Editors for

each Section, (f) form of publications of Union, (g) policy as to free distribution of publications, (h) question as to allowance for travel expenses of paid Executive Secretary and possibly officers of Sections to attend meetings, and (i) appointment of a Special Committee to recommend and select or appoint a man to take the position as paid Executive Secretary, consideration being given to engagement for a specified period, subject to satisfactory services, and rate of compensation.

It was moved, seconded, and carried that a Special Committee be appointed by the President of the Union to consider the various items listed above and to report to a special meeting of the Executive Committee, to be called at an early date.

Proposed Geological Council of America--After extended discussion of Dr. A. I. Levorsen's letter of April 3, 1944, and its enclosures, copies of which had been sent all Members of the Executive Committee, a motion was made, seconded, and carried that two Members of the Union be sent to observe and study the purposes of the proposed Council of Geological Organizations at a meeting to be held probably in New York, and report back to the Executive Committee of the Union. E. Cloos and A. Blake were appointed by President Lowdermilk to act as observers at this meeting.

The meeting adjourned at $17^h\ 30^m$.

Jno. A. Fleming
General Secretary

Minutes of June 29, 1944

The meeting was called to order at $14^h\ 00^m$ by President Lowdermilk in the Library of the Cosmos Club, Washington, D. C. The following persons were present:

Present--L. H. Adams, L. P. Disney, J. A. Duerksen, J. A. Fleming, H. D. Harradon, H. F. Johnston, W. D. Lambert, W. C. Lowdermilk, J. P. Marble, H. E. McComb, A. G. McNish, F. Neumann, J. W. Peoples, C. S. Piggot, F. W. Reichelderfer, I. Roman, W. L. Schmitt, C. H. Swick, C. W. Thornthwaite, and R. M. Wilson. A. F. Buddington, J. E. Church, E. Cloos, L. P. Eisenhart, R. M. Field, N. H. Heck, C. R. Longwell, G. W. Musgrave, L. L. Nettleton, W. W. Rubey, V. C. Stechschulte, H. T. Stetson, H. U. Sverdrup, W. T. Thom, Jr., and T. G. Thompson were excused because of absence from the city or previous engagements.

Minutes--Minutes of the previous meeting of June 2, 1944, have not yet been distributed and consideration of them was postponed until later.

General Secretary's Report

Because of the urgency of the other business as noted in the letter calling the meeting, the General Secretary's report was limited to a few items as follows:

Finance--A preliminary financial statement from January 1, 1944, to June 28, 1944, was submitted and the General Secretary was authorized in transmitting the minutes of the meeting of June 29 to amplify this report so that it would include receipts and disbursements through the end of the fiscal year, June 30, 1944.

Membership--The General Secretary reported that there had been one objection only to the Members and Associate Members proposed in the lists of June 15 and 21, namely, Richard Fenley Hunter; after consideration and discussion the Committee voted unanimously that Mr. Hunter should be elected to full membership, and that the election of the others listed either as Members or Associate Members be confirmed. The total membership as of June 30, 1944, is 2179 after taking account of added names, deceased Members, resignations, and transfers to inactive list from May 28, 1944, as listed below.

(I) Newly-elected Members (33)

Robert N. Bills	Richard Martin Foose	Richard Fenley Hunter
Charles Jonas Cohen	William Frederick Foshag	Ross Nebolsine
Lorenzo Donald Doty	Charles Frederick Feuchsel	Leonard Joseph Newman
Rex Alfred Elder	Ralph W. Gemmer	Charles Harold Pierce
Robert Dunshee Eliott	Frederick R. Gracely	William S. Pike, Jr.
Frank Shaw Farquhar	James H. Hartwell	Helen Fenwick Pool
D. Jerome Fisher	Herbert Hoover, Jr.	Donald A. Rice

(I) Newly-elected Members--Concluded

Claude Martine Roberts	R. H. Schmuck	James Henry Taylor
Oscar Rosenzweig	Ernest T. Schuleen	G. Oscar Villeneuve
John V. Salo	Karl Stefansson	Girard E. Wheeler
Ivan Victor Scherb	Archie Carter Swearingen	Donald Edward White

(II) Newly-elected Associate Members (3)

Robert William Chesney	E. Davis	A. Delbert Peterson

(III) Deceased (2)

J. H. Ryan, July 10, 1943 — Harry Fielding Reid, June 18, 1944

(IV) Resigned (2)

A. J. Gillardi, June 19, 1944 — E. H. Bourquard, June 26, 1944

(V) Inactive List (4)

John M. Lanning, June 3, 1944 — Wayne I. Travis, June 24, 1944
Otto B. Van Horn, June 9, 1944 — Norman T. Riffe, June 26, 1944

(VI) Dropped for non-payment of dues

None

Summary of membership as of June 30, 1944

Members and Associate Members (including 2 Honorary Members)	2161
Members in Axis-controlled countries, retained in active list by action of Executive Committee	10
Corresponding Members	4
Ex-officio Members (5 less 1, included above)	4
Total, including ex-officio Members	2179

Special Fund--After hearing the General Secretary's report on the state of the Special Fund, it was moved and carried that the balance on hand in the name of the Washington Assembly, $1,513.77, together with $6.23, from the Union's reserve, to make a total of $1,520.00, be transferred to the Special Fund account with the understanding that such obligations as have been previously carried on account of Washington Assembly matters be assumed for future payment so far as is necessary through the Union. It was noted that this balance was considerably less than the total which had been received as registration fees from Americans only on the occasion of the Washington Assembly. With other contributions already received and those received during the meeting, the grand total in full realization of the Special Fund is now $10,005.00, and thus, in accordance with the report of Chairman Field of the Committee on Finance, the Special Fund is complete.

Publications--The General Secretary was authorized to ask the Committee on Membership to revise the general circular prospectus of the Union for distribution to prospective Members and upon the receipt of the revised copy to print the same in an edition sufficient to meet the expected needs.

Rockefeller Foundation Grant--The General Secretary summarized briefly the requirements of the Rockefeller Foundation for the receipt and expenditure of the sum of $20,000 as a three-year grant beginning July 1, 1944, and was instructed to make such arrangements as necessary meeting the requirements of the National Research Council and the Foundation as regards receipts and expenditures against the grant.

International Union of Geodesy and Geophysics--The General Secretary reported that on June 14, 1944, there had been received from the Treasurer of the United States, in payment of the dues for adherence of the United States to the International Union of Geodesy and Geophysics for the calendar year 1943, the sum of $3,920.40, which had been deposited with the Riggs National Bank in the account of the International Union, and that as of June 29, 1944, the balance in the account in the Riggs National Bank was $18,093.72. The General Secretary stated that, in accordance with the action of the Executive Committee on June 2, he was taking up with the financial officers of the National Research Council the necessary authorization for investment of part of this balance in United States series G war bonds.

Special Committee on Policy of the Union--The appointment by the President of a Special Committee on Policy of the Union was announced as follows: H. F. Johnston (Chairman), W. H. Bucher,

W. G. Hoyt, F. W. Reichelderfer, and C. H. Swick, with the indication of J. A. Fleming, N. H. Heck, and W. C. Lowdermilk as ex-officio members for consultation.

New Business

Report of Special Committee on Policy of the Union--Chairman Johnston presented the report of the Special Committee on Policy of the Union. This report was discussed in great detail and finally unanimously adopted and approved as follows:

Report of Special Committee on Policy of the Union

W. H. Bucher W. G. Hoyt H. F. Johnston (Chairman)
F. W. Reichelderfer C. H. Swick

The Statutes of the American Geophysical Union as originally adopted in 1919 gave in broad outline its purpose and constitution, and that they are sufficiently elastic is proven by the minor revisions that have been necessary. The Executive Committee has governed the Union since its inception, and its formal decisions have been implemented by the General Secretary. Fortunately indeed for the Union, its General Secretary for many years has been Dr. John A. Fleming, who has given unstintedly of his time and planning ability with the result that the major part of the steady progress of the Union has been due to his efforts.

Having accomplished our aim of raising $30,000 for the Special Fund to be expended during the next three years, new arrangements are necessary and plans must be laid for its disbursement. Your Special Committee had a meeting yesterday at which W. G. Hoyt, H. F. Johnston (Chairman), F. W. Reichelderfer, and C. H. Swick were present. They had previously had the advantage of conversations with Messrs. J. A. Fleming, N. H. Heck, and W. C. Lowdermilk, the ex-officio members of the Committee, who from their long experience in matters relating to the Union's past activities were able to give valuable advice. The Chairman also talked with Dr. W. H. Bucher last night by telephone, and his suggestions are included.

Your Committee is conscious of the many problems which will confront the Union in the next three years but is confident that satisfactory solutions will be evolved. The greater portion of the problems will be met in the next year and your Committee therefore suggests that every member of the Executive Committee furnish written comments and suggestions at frequent intervals to the General Secretary's office and that the General Secretary will inform the members of the Executive Committee of the problems arising as often as is necessary.

Your Special Committee recommends the following actions from a broad point of view.

General Secretary--The General Secretary elected by the Union will, as heretofore, be responsible to the Executive Committee and see that its wishes are fulfilled. He will exercise general supervision over the Executive Secretary and serve without honorarium. The more important letters of the Union must be signed by the President or General Secretary. The General Secretary, as heretofore, will receive and disburse the funds of the Union.

Executive Secretary--The Executive Secretary shall be responsible to the General Secretary and, with the assistance of such clerical help as is necessary, will perform all the executive duties as indicated by the General Secretary, acting for the Executive Committee. The selection and appointment and compensation of the Executive Secretary will be accomplished by a small Special Committee of five to include the President, Vice-President, and General Secretary of the Union. The rate of compensation for the Executive Secretary is tentatively suggested as $4,000 per annum.

Transactions--In view of the conflict which might arise by the use of the title American Journal of Geophysics with the publications of other societies and in view of the wide-spread knowledge of the Transactions of the Union over many years, it is considered that the publications of the American Geophysical Union should retain the title of Transactions of the American Geophysical Union of the National Research Council, using suitable part and volume (year) designations.

Editorial Board--It is recommended that the control of the matter to be published in our Transactions rest in an Editorial Board with General Secretary ex-officio a member to act as Chairman and with at least one member from each Section of the Union, the Section of Hydrology being represented by perhaps three and the Section of Meteorology by two. The Section members of the Editorial Board are to be nominated by the Executive Committee of the particular Section. The Editorial Board shall have responsibility for the acceptance, revision, condensation, or re-

jection of any manuscript submitted for publication. The General Secretary will be charged with the responsibility of securing the desired condensation of any paper and of informing the author in the case of rejection. In the case of minor revision of a paper, the Editorial Board will deal directly with the author. The Editors for respective Sections may receive honoraria in accordance with an approved budget.

Free distribution of publications--It is recommended that a Special Committee be appointed to consider the list of libraries, organizations, and individuals to whom the Transactions should be supplied without charge.

Allowance for travel expenses--It is recommended that a modest amount as set by the budget be allocated for the expenses of travel of the Executive Secretary to be expended under the control of the General Secretary of the Union.

Special Committee for Selection, Appointment, and Compensation of an Executive Secretary--After conferring with incoming President Adams, President Lowdermilk appointed the following Committee in accordance with the action taken in the report of the Special Committee on Policy of the Union: L. H. Adams, W. H. Bucher, J. A. Fleming, W. G. Hoyt, and H. F. Johnston.

Budget--Chairman Swick presented the report of the Committee on Budget as regards a budget for the fiscal year July 1, 1944, to June 30, 1945. After consideration and discussion of each item, the budget was approved in the final form as per attached copy.

Expression of Appreciation to the Carnegie Institution of Washington--Upon motion duly seconded it was unanimously agreed that a resolution should be prepared by the Chairman of the Committee on Resolutions for the Twenty-Fifth Annual Meeting to express to the Carnegie Institution of Washington the grateful appreciation of the Union for the facilities extended these many years to the Union in the provision of space for office and storage at the Institution's Department of Terrestrial Magnetism.

The meeting adjourned at $16^h\ 30^m$.

Jno. A. Fleming
General Secretary

Financial Statement January 1 to June 30, 1944

Receipts			
Cash balance, January 1, 1944, as reported from December 31, 1943			$10,487.31
American Geophysical Union		$5,872.94	
Special Fund		2,905.00	
Bowie Medal Fund		195.60	
Washington Assembly		1,513.77	
Dues, 1941, 1942, 1943, 1944, 1945, 1946			5,408.00
1941		$ 3.00	
1942		21.00	
1943		148.00	
1944		5,213.00	
1945		19.00	
1946		4.00	
Sales of Publications			- 1,260.42
Transactions	$ 779.51		
Reprints	1,451.69		
Bibliography of Hydrology	6.01		
List of Members and Officers	1.90		
Exhibit Maps	4.00		
Proceedings Geodesy, Washington Assembly	2.70	$2,245.81	
Transfers to Special Fund by Executive Committee			
June 2, 1944	$3,500.00		
June 29, 1944	6.23	- 3,506.23	
Forwarded			$14,634.89

Receipts--Concluded		Forwarded	$14,634.89
Special Fund			7,100.00
Contributions		$2,080.00	
Transfers by Executive Committee		5,020.00	
June 2, 1944	$3,500.00		
June 29, 1944	6.23		
June 29, 1944, balance Washington Assembly	1,513.77		
Washington Assembly balance			- 1,513.77
Balance		$1,513.77	
Transfer by Executive Committee June 29, 1944		1,513.77	
National Research Council			167.46
Miscellaneous			0.95
Total receipts ($10,487.31 + $9,902.22)			$20,389.53
Disbursements			
Transactions of 1943			$ 3,833.61
Reprints			1,173.16
Expenses of General Secretary's Office			1,498.03
Services, including income tax		$1,378.63	
Miscellaneous		119.40	
Committees			43.75
Finance		$17.25	
Membership		26.50	
Sections			93.64
Geodesy		$21.91	
Seismology		3.60	
Meteorology		22.90	
Terrestrial Magnetism and Electricity		1.95	
Oceanography		1.80	
Volcanology		1.80	
Hydrology		30.00	
Tectonophysics		1.90	
Berkeley Regional Meeting Account		7.78	
Annual Meeting (postage mailing sectional notices)			412.12
Postage, express, telephone, and telegraph			638.03
Stationery, supplies, and miscellaneous			187.67
Bowie Medal			10.00
Total disbursements			$ 7,890.01
Balance June 30, 1944			$12,499.52

Distribution of balance

Riggs National Bank, Chevy Chase Branch, including $100.50 in checks not deposited.		$12,499.52
American Geophysical Union	$ 2,308.92	
Special Fund	10,005.00	
Bowie Medal Fund	185.60	
Washington Assembly	0.00	
Bills receivable		
Publications		$ 491.99
Transactions	$334.00	
Reprints	136.39	
Miscellaneous	21.60	
Dues		1,632.00
Postponed account, 10 Members in enemy country	$ 99.00	
Unpaid account, 33 Members for 3 years, 1942-1944	297.00	
Unpaid account, 43 Members for 2 years, 1943-1944	258.00	
Unpaid account, 326 Members for 1 year, 1944	978.00	
National Research Council allotment for fiscal year ending June 30, 1944		232.54
Total bills receivable		$ 2,356.53
Bills payable (estimated to June 30, 1944)		
Annual Meeting		$ 149.50
Postage, telephone, telegraph, miscellaneous		133.04
Total bills payable		$ 282.54

Recapitulation

	A.G.U.	Bowie Medal Fund	Special Fund
Cash balances	$2,308.92	$185.60	$10,005.00
Bills receivable	2,356.23	0.00	0.00
Total	$4,665.15	$185.60	$10,005.00
Bills payable (estimated)	282.54	0.00	0.00
Net (estimated)	$4,382.61	$185.60	$10,005.00

Budget for the Fiscal Year July 1, 1944, to June 30, 1945

Adopted after Consideration of Report of Committee on Budget [C. H. Swick (Chairman), H. N. Eaton, G. W. Goranson] at the Regularly Called Meeting of the Executive Committee of the Union, June 29, 1944

Receipts		
Balance in bank, June 30, 1944	$12,404[b]	
Dues 2,100 (net[a]) Members for 1945	6,300	
Grant National Research Council	400	
Grant Rockefeller Foundation account	6,000[c]	
Sales Transactions and reprints	1,700	
Sales miscellaneous	200	
Bills receivable July 1, 1944, for 1944 dues and publications	1,352[d]	
Total estimated receipts		$28,356
Deduction for reserve, Special Fund		6,667
Net available receipts		$21,689
Expenditures		
Cost Transactions complete (800 + pages)	$ 4,300	
Cost Bibliography of Hydrology, 1941-1944	350	
Cost List of Members and Officers	300	
Services Executive Secretary	5,000	
Services three clerks	5,400	
Expenses Twenty-Sixth Annual Meeting	500	
Expenses Regional Meetings	250	
Expenses Committees	150	
Honoraria to Co-Editors for eight Sections	2,000	
Postage and communication	600	
Stationery and miscellaneous	500	
Office equipment	300	
Travel	300	
Bills payable July 1, 1944	50	
		20,000
Estimated balance June 30, 1945		$ 1,689[e]

[a] Although we now have nearly 2,200 Members with excellent prospect of additions during the year, effects of war causing resignations and non-payment of dues make it wise to set expected net of dues as for 2,100 Members.

[b] This includes $10,000 contributed to the Special Fund by Members; it is to be noted that but one-third of the $10,000 may properly be expended during the year and that we must reserve two-thirds of $10,000 from balance as of June 30, 1945.

[c] To be requisitioned in four quarterly installments.

[d] This item assumes that a certain amount of past dues will not be paid because of resignations, overseas duty, and dropping of any becoming two years in arrears.

[e] In addition to this balance there will also be the cash reserve balance in the Special Fund of $6,667, as indicated under Receipts.

APPENDIX C--REPORT OF COMMITTEE ON MEMBERSHIP, 1943-44

G. W. Musgrave, Chairman

L. P. Disney (Oceanography)	H. F. Johnston (Terrestrial Magnetism and Electricity)
J. A. Duerksen (Geodesy)	J. B. Mertie (Volcanology)
L. P. Harrison (Meteorology)	Waldo E. Smith (Hydrology)
Earl Ingerson (Tectonophysics)	F. W. Sohon (Seismology)

Though wartime activities as well as the recent financial campaign have had their effects upon the work of the Committee, progress nevertheless has been made. Three hundred and seven new Members were added during that period. The total growth was 16 per cent and the net growth about 13 per cent.

Many of these new Members are traceable to the interest and activity of the membership at large. For example, to one Member of the Union alone (and one who is not a member of this Committee) there is traceable more than a score of new Members. Such activity shows the real interest which Members have in the welfare of the Union.

Direct individual application on the part of an interested individual is rare. Because of our requirements for sponsorship, many qualified individuals are reluctant to make application without having a personal invitation to do so. Indeed, in many instances, it would be difficult for such individuals to know where to secure sponsors, since they do not have available a list of our Members. The personal invitation by a Member of the Union surmounts this difficulty and also has within it an element of selection and some assurance that the applicant is qualified for one of the classes of membership. From every angle the activity of the membership at large is most valuable and constructive and should be encouraged to the fullest extent. The Committee would like to keep all Members of the Union continuously supplied with blank proposal forms so that the splendid work which they are doing could be continued with a minimum of effort on their part. It is hoped that the habit of contacting colleagues may become a fixed habit because from it stems the life-blood of the Union.

At a recent meeting of the Committee consideration was given to areas where there is a deficit of membership--those States and areas where our representation is disproportionately low but which at the same time are areas noted as producers of scientific men. Such States, for example, as Ohio, Indiana, Illinois, Iowa, Missouri, Minnesota, Michigan, Pennsylvania, and Connecticut, have a disproportionate representation and appear to be promising fields for enlarging activities of the Union. Several possible plans of action for work in these States are under consideration. Some eleven other States have both a relatively small Union population and also a small rate of growth and are deserving of special attention by the Committee.

Numerous members of the Committee have devoted many hours of effort to compiling lists of qualified men, to correspondence, to attendance upon meetings of the Committee, and to similar matters--items which in many instances were an overburden on an already excessively loaded wartime schedule. Much of our growth has come from such work. It is impossible to adequately recognize and give sufficient credit for the personal time and thought so generously donated to the Union by so many individuals.

APPENDIX D--REPORT OF COMMITTEE ON BUDGET, 1943-44

C. H. Swick, Chairman

R. W. Goranson H. N. Eaton

Your Committee on Budget wishes to submit the following proposed budget for the fiscal year July 1, 1943, to June 30, 1944:

Expected receipts		
Balance in bank June 30, 1943	$7,293.75[b]	
Dues, 1,850 (net[a]) Members for 1943	5,550.00	
Grant, National Research Council	400.00	
Sales, Transactions and reprints	1,700.00	
Miscellaneous	100.00	
Total estimated receipts		$15,043.75
Authorized expenditures		
Cost 1943 Transactions complete (700+ pages)	$4,300.00[c]	
Cost 1941-42-43 Bibliography of Hydrology	0.00[d]	
Cost List of Members	375.00[c]	
Clerical services, including full-time stenographer in General Secretary's office and for Sections	2,500.00	
Expenses 25th Annual Meeting	400.00	
Expenses Regional Meetings	150.00	
Committee expenses	400.00	
Postage (Transactions, reprints, office)	500.00	
Stationery and miscellaneous	500.00	
Reserve for contingencies, initiation of American Journal of Geophysics, and balance	5,918.75	
Total estimated expenditures		$15,043.75

[a]Although we now have 2,000 Members with excellent prospect of additions during the year, effects of war causing resignations and non-payment of dues, makes it wise to set net of dues as for 1,850 Members.

[b]Exclusive of (a) Bowie Medal Fund $195.60, (b) Special Fund $261.00, and Washington Assembly balance of $1,513.77 (for which there are liabilities authorized of equal amount).

[c]The Executive Committee on November 20, 1943, voted to increase the recommended item for Transactions from $3,500 to $4,300 and the one for List of Members from $250 to $375. These increases were required because both publications were to be increased in size and because costs of printing were higher. A corresponding decrease had to be made in the item for reserve.

[d]Probably no manuscript will be prepared for edition of 1941-43 until after war; if prepared, cost will be equalled by sales.

At the meeting of the Executive Committee on November 20, 1943, the Committee on Budget was instructed to submit a recommendation as to the amount of the reserve funds of the Union that might safely be allocated to the Special Fund which is now being raised to provide a paid Secretary and to inaugurate the proposed Journal of Geophysics.

After consultation with the General Secretary and after careful consideration of the financial status of the Union, the Committee on Budget recommended that $2,500 be allocated to the Special Fund, with the possibility of increasing the amount to $3,000 if the Executive Committee deemed it advisable to operate the Union, temporarily at least, with a rather small reserve. The net assets of the Union as of January 1, 1944, were $4,241.

[Note: For Budget for the fiscal year July 1, 1944, to June 30, 1945, in form finally approved by Executive Committee at its meeting on June 29, 1944, see page 342.]

APPENDIX E--REPORT OF SPECIAL COMMITTEE ON FINANCE, 1943-44

R. M. Field, Chairman — G. W. Musgrave, Vice-Chairman
J. A. Fleming (ex-officio) — K. C. Heald — W. W. Horner

Your Committee was instructed by the Executive Committee of the Union to raise $30,000 The Committee reported at the Twenty-Fifth Annual Meeting of the Union that it had completed its task and that by early summer (1944) the total amount would have been raised. The total for account of the Special Fund in cash as paid into the treasury of the Union by Members and Friends is shown in Table 1.

Table 1--Amounts received for Special Fund with number of individual contributors and Chairmen of Sub-Committees for the eight Sections of the Union

Section	Quota[a]	Received to June 30, 1944		Received after June 30, 1944		Chairmen Sub-Committees on Finance
		Total	No. contributors	Total	No. contributors	
(a) Geodesy	$ 900	$ 946.00	98	$	...	C. L. Garner
(b) Seismology	1,000	1,065.50	128	.....	...	O. W. Swainson
(c) Meteorology	1,800	1,013.00	137	2.00	1	J. Namias
(d) Terrestrial Magnetism and Electricity	900	1,664.00	135	7.00	2	H. F. Johnston
(e) Oceanography	900	886.00	106	.....	...	W. G. Watt[b]
(f) Volcanology	600	968.00	80	.....	...	A. F. Buddington
(g) Hydrology	2,900	2,354.50	322	5.00	1	W. G. Hoyt
(h) Tectonophysics	1,000	1,108.00	141	.....	...	E. Cloos
Totals.....	$10,000	$10,005.00	702[c]	$14.00	4	

Grand total $10,019.00 in 706 contributions

[a]The quotas listed are the respective amounts which each Section might have been expected to raise upon the basis of its affiliations. [b]Succeeding A. H. CLARK, April 15, 1944. [c]Total number of individual contributions and not total of figures in column; many individuals were affiliated with several Sections.

Attention should be called to the contribution of Theodore Wentworth of $500 and to the contribution of the Western Snow-Conference of $100.

Dr. F. B. HANSON, Associate Director for the Natural Sciences of The Rockefeller Foundation, stated that as many contributors as reported above, namely, over 30 per cent, is most unusual, especially when entirely on a voluntary basis. "Unusual" or not, the per capita contributions are evidence of the strong interest of the Members in their Union, and of the efficiency and sense of responsibility of all Chairmen of all Sub-Committees of all Sections.

Contribution to Special Fund received from the Rockefeller Foundation

In late 1943 the Chairman of the Special Committee on Finance had an informal conference on the National and International responsibilities of the American Geophysical Union with THOMAS B. APPLEGET, Vice-President of The Rockefeller Foundation. Shortly afterward the Chairman and Dr. JOHN A. FLEMING held two conferences (1) with Mr. APPLEGET and (2) with Dr. FRANK B. HANSON, Associate Director for the Natural Sciences of the Foundation. As a result of these conferences, an application dated April 12, 1944, for financial aid (in a total of $20,000 over three years from July 1, 1944) was prepared and signed by the President, Vice-President, and General Secretary of the Union. That application, after approval of the National Research Council and of the Council of the National Academy of Sciences, was transmitted on May 2, 1944, to the Foundation for the attention of the Director for the Natural Sciences (Dr. WARREN WEAVER).

That the record may be complete, the pertinent correspondence and the application are printed here.

Letter of April 21, 1944, from General Secretary to Dr. W. H. KENERSON, Executive Secretary of the National Research Council--In accordance with telephone conversation this morning, I am sending you herewith two copies of the revised form of application to The Rockefeller Foundation for financial aid. Please replace the two copies that Dr. Lowdermilk and myself left with you at our recent conference with these. The exhibits are the same as those which were supplied you originally, and so no copies of exhibits are enclosed.

We are all in high hopes that the Council of National Academy of Sciences will take favorable action upon the recommendation of National Research Council.

Letter of April 28, 1944, from Dr. ROSS G. HARRISON, Chairman of the National Research Council, to the General Secretary--Attached is a copy of the action taken by the Council of the National Academy of Sciences on recommendation of the National Research Council concerning the acceptance and administration of funds for the support of activities of the American Geophysical Union.

Letter of April 28, 1944, from PAUL BROCKETT, Executive Secretary of the National Academy of Sciences--The Council of the National Academy of Sciences, at its annual meeting April 23, 1944, approved the following recommendation from the National Research Council:

"... that the Research Council be authorized to accept and administer funds to the amount of $20,000 to be available over a period of three years beginning July 1, 1944, for the support of activities of the American Geophysical Union. The Union proposes to make application for a grant in the above amount from The Rockefeller Foundation, contingent upon the Union itself providing an additional sum of $10,000. The purpose, as outlined by the officers of the Union, is 'to give greater support to the advancement of international and national coordination for research on natural phenomena of Earth processes (geophysics), and interpretations and applications thereof for human welfare.'"

Letter of May 2, 1944, from the Officers of the American Geophysical Union to The Rockefeller Foundation for attention of the Director for the Natural Sciences--Following the informal discussions of officers of the American Geophysical Union with Vice-President Appleget in December, 1943, and Associate Director Hanson in March, 1944, we have, upon the authorization of the Executive Committee of the Union, prepared an application to The Rockefeller Foundation for financial aid. We have deferred sending the application until there was opportunity for consideration in detail by the National Research Council and by the annual meeting of the Council of the National Academy of Sciences. As indicated by the attached copies of letters, under date April 28, (a) from the Executive Secretary of the National Academy of Sciences, and (b) from the Chairman of the National Research Council, both NRC and NAS approved the principle and plan proposed and endorsed the request. The application as of date April 12, 1944, of which copies were considered by NRC and the Council of NAS, together with three exhibits, all in duplicate, are enclosed herewith.

If you have any queries relating to items listed, or other matters, we shall be happy to write you in more detail, or, if you prefer, have one or more of the officers call at your office in New York at any time convenient to you for conference. We may say that the total contribution from members of the Union now actually in hand is $8,000, and that the balance is expected to be available on or before June 15.

Thank you for such consideration as you may find it possible to give this application.

Application to The Rockefeller Foundation for financial aid

The American Geophysical Union hereby makes application to The Rockefeller Foundation for financial aid to total $20,000 in three years (July 1, 1944, to June 30, 1947), contingent upon provision by the Union itself of $10,000 to make a grand total of $30,000. The aid is to give greater support to the advancement of international and national coordination for research on natural phenomena of Earth processes (geophysics), and interpretations and applications thereof to human welfare.

The following paragraphs summarize briefly the reasons for this application as authorized by the Executive Committee of the Union.

History and functions--The American Geophysical Union (AGU) was created in 1919 as an Executive Committee by the National Research Council of the National Academy of Sciences (NRC NAS) to function as the American National Committee for the International Union of Geodesy and Geophysics (IUGG) and the Committee on Geophysics of the NRC. Its defined duties are "to promote the study of problems concerned with the figure and physics of the Earth, to initiate and coordinate researches which depend upon international and national cooperation, and to provide for their scientific discussion and publication." These duties are organized under eight Sections of the Union: Geodesy; Seismology; Meteorology; Terrestrial Magnetism and Electricity; Oceanography; Volcanology; Hydrology; and Tectonophysics (these fields are briefly described in the attached pamphlet marked Exhibit A).

The original limit in number to 100 or less held until April 1930 and was then removed by action of NRC. From 1919 to 1931 funds required for the expenses of the Union were provided by NRC. Because of the rapid growth and extension of interests it was arranged from 1932 that annual contributions ($2 until 1937 and $3 since then) be made by each person associated and the annual aid from NRC was reduced to $400. More than 2,100 qualified persons are now collaborating as annual contributors; of these over 700 were enrolled during 1942 and 1943.

National responsibilities--AGU serves national interests in its specified duties in coordinated fact-finding and applications of dynamics of earth-sciences in part through (1) annual meetings (24 so far in Washington) for presentation and discussion of scientific papers and progress-reports in the eight branches of geophysics and their interrelations and interpretations, and (2) regional meetings (16 since 1934 in seven western, mid-western, and southern states) for similar agenda. These meetings, appraised by competent authorities as most stimulating and profitable, afford unique opportunities for contact and discussion among leading investigators and for promotion and development of knowledge and application in the related fields. Communications are

received not only from the United States but also from Canada, Mexico, Central America, and some of the South American countries. The rapidly increasing knowledge in geophysics from the forecasting of dynamics of soil erosion, cosmic relations of radio wave-propagation, to forecasting water resources from snow surveys and their applications within the past few years has enlarged the responsibilities of the Union in national progress.

International responsibilities--AGU serves international interests in studies of natural Earth forces that condition human endeavor and progress in making use of Earth's resources, of land, of minerals, and of water, and must have world-wide coordination of effort, that is, cooperation which is unrestricted by national boundaries. AGU has taken prominent part, through designation of delegates by NAS upon recommendation of NRC, to the triennial assemblies of the IUGG. (So far seven triennial assemblies have been held, namely, at Rome in 1922, Madrid in 1924, Prague in 1927, Stockholm in 1930, Lisbon in 1933, Edinburgh in 1936, and Washington, D. C., in 1939.) These meetings have coordinated and stimulated international plans and efforts. With the advent of war AGU has been an important factor in maintaining continuity of international activities, which otherwise would have lapsed, thus insuring normal and effective postwar rehabilitation of IUGG. In particular, AGU has taken part in enlarging the interest and participation of the other countries of the Western Hemisphere in geophysics.

Publications--AGU serves science by advancing knowledge and facilitating application of the dynamics of Earth forces and materials through a complete record of scientific papers, discussions, and reports at annual and regional meetings of the AGU in the annual Transactions of which 20 volumes have been published--six during 1919-29 and 14 since 1930. Through the method of offset printing directly from prepared copy, the all-inclusive cost of publication has been remarkably low and has averaged in a total of some 9,200 pages since 1930 (equivalent to at least 14,000 pages in the usual conventional printed format) slightly over $3 a page in editions of 2,000 to 2,600, a rate less than one-quarter of the cost for ordinary letter-press printing. The volumes are distributed free of charge to every person enrolled in the Union, to reviewing journals and libraries, and to between 300 and 400 geophysicists and interested organizations and libraries abroad. (A copy of Part II of the Transactions of 1943, issued in January 1944, is attached as Exhibit B.) Other publications include five volumes concerned with the Washington Assembly of IUGG. Thus far the editing and preparation of master-copy for publication has been done gratuitously in the spare time of officers of the Union, particularly its General Secretary.

Opportunity--The opportunity for enlarged service to our national and international contributions in Earth sciences is almost boundless. Typical examples of the Union's usefulness in obtaining international and national cooperation are:

(1) Two naval expeditions to the Caribbean already completed which would hardly have been attempted by private organizations and which represented a cost equivalent to hundreds of thousands of dollars in the use of surface and sub-surface vessels and scientific personnel and equipment made available--largely upon the Union's solicitation--by governmental and research organizations (United States Navy, Department of State, American Telephone and Telegraph Company, Princeton University, Carnegie Institution of Washington, Woods Hole Oceanographic Institution, the Dutch Government, and others; see attached copy (Exhibit C) of bathymetrical chart prepared by the Hydrographic Office of the United States Navy and its legend).

(2) Just before the outbreak of the war the Union, in collaboration with the National Geographic Society and the University of Virginia, had obtained authority for the use, during one year, of a Coast Guard 300-foot cutter with complete complement of men, and had secured scientific personnel and equipment from various research organizations for extensive geophysical and biological surveys in the area of the South Pacific Islands, all at no actual financial outlay, and with the gratuitous services of scientific investigators--a unique example of use of facilities which may come from use of those available but not coordinated. The large practical and scientific additions to knowledge that would have resulted, had not the war interfered just when arrangements had been made and equipment in large measure delivered on the west coast, can hardly be estimated.

(3) AGU has not only stimulated organization of major expeditions, as in (1) and (2), for the accumulation of needed data, but has also been active in fostering comparable analyses and diffusion of new facts thus obtained. This has been partly brought about through the Union's cooperation in sponsorship and presentation of joint symposia; examples are (a) "The geophysical exploration of the ocean bottom" with the American Philosophical Society, and (b) "The surface and sub-surface exploration of continental borders" with Sections D and E of the American Association for the Advancement of Science.

It is this type of "catalytic" functioning in many fields which AGU can bring about at comparatively little actual expenditure and without burden upon scientific endowments.

Effect of war--The war has greatly increased the demands upon the resources of AGU by reason of (1) increased costs, (2) increased number of associates in the armed forces and the consequent increased burden upon those available to continue essential and expanding operations--not only because of applications to the war effort but also the rapidly enlarging potential applications in postwar progress--and (3) increased need of maintenance to safeguard continuation of international progress and cooperative effort.

Present needs--The continued and future success of AGU depends upon (1) publication of Transactions, (2) moderate financial aid besides that contributed by its present 2,100 associates to overcome the handicap caused by the abnormal conditions of war, and (3) a paid full-time Executive Secretary. To meet these pressing needs the AGU planned in 1943 to establish a financial basis consonant with the opportunities to advance geophysical knowledge and applications in both international and national undertakings. To this end additional special voluntary contributions from associates were solicited in a total of $10,000 (of which $7,000 is already received) toward the estimated goal of $30,000 required for the three years from July 1, 1944, to June 30, 1947. By 1947, and with the return of normal conditions, the number of persons associated with AGU will have so increased that the annual contributions will fully meet expenses of maintenance and future development.

The contribution of voluntary services has become such a heavy burden under existing conditions with the increasing responsibilities of AGU that it cannot equal the need. Continued and enlarged functioning of AGU in keeping with the growing opportunity requires a full-time paid Executive Secretary and additional funds other than those received annually from associates.

Résumé

For the purpose of serving more effectively the sciences dealing with the Earth itself and of ultimately applying such knowledge more efficiently to the advancement of human interests, the American Geophysical Union wishes to place its operations on a more nearly independent footing, and for this purpose is asking a grant of $20,000 to supplement the $10,000 now being raised by voluntary contributions. It is expected that, once the Union is functioning in the desired manner, it can thenceforth be entirely self-supporting.

Letter of May 5, 1944, from Dr. FRANK BLAIR HANSON, Associate Director for the Natural Sciences of The Rockefeller Foundation, to President LOWDERMILK--This will acknowledge receipt of your letter of May 2 with supporting material for the request of the American Geophysical Union to The Rockefeller Foundation for the sum of $20,000. This request will be presented to our Board on May 19. I am sure you will understand that it is not possible to give any indication of what action may be taken until the Trustees have had opportunity for consideration and thorough discussion of the request.

Letter of May 19, 1944, from Miss NORMA S. THOMPSON, Secretary of The Rockefeller Foundation, to President LOWDERMILK--I have the honor to inform you that at a meeting of the Executive Committee of The Rockefeller Foundation held May 19, 1944, action was taken providing up to $20,000 to the National Research Council for the expenses of the American Geophysical Union during three years beginning July 1, 1944, the amount to be available in any one year of the grant not to exceed $10,000. It was the understanding of the meeting that these funds would be used to pay the salary of a full-time secretary for the Union and for other expenses for a period during which attempts will be made to add sufficiently to its membership to carry overhead expenses in the future.

If it meets with your convenience, payments will be made on a quarterly basis upon the receipt at the beginning of each year of a copy of the budget. We would also ask that annual statements of receipts and expenditures be sent us. Any balance remaining unexpended as of June 30, 1947, will revert to the Foundation.

Letter of May 27, 1944, from President LOWDERMILK to the Secretary, The Rockefeller Foundation--On behalf of the Executive Committee and of the membership of the American Geophysical Union, I want to thank you for your letter of May 19 informing us of the action taken by the Executive Committee of The Rockefeller Foundation on that date. We note that $20,000 will be made available to the National Research Council for expenses of the American Geophysical Union during three years beginning July 1, 1944, the amount to be available in any one year of the grant not to exceed $10,000.

It will be quite convenient to the American Geophysical Union to receive payments on a quarterly basis after submission at the beginning of each year of a copy of the budget. We shall be glad to comply with your request for an annual statement of receipts and expenditures, copy of which we will also submit to the National Research Council.

We expect to have by July 1, 1944, the sum of $10,000 raised by the membership of the American Geophysical Union to add to the grant of $20,000 by The Rockefeller Foundation, the total of which we count as sufficient for the employment of a full-time secretary-editor and for other expenses.

Our membership has grown rapidly during the past three years, and more and more active interest is being shown in the eight sections of geophysics and in the Transactions of the Union. We are especially pleased with this increase in interest and contributions even in time of war and look forward to an even greater growth with the assistance The Rockefeller Foundation has been good enough to make available to us.

R. M. FIELD, Chairman
For the Committee

APPENDIX F--REPORT OF SPECIAL COMMITTEE ON NATIONAL WELFARE AND RELATED FUNCTIONS, 1943-44

Richard M. Field, Chairman

Louise A. Boyd	R. F. Griggs	R. A. Millikan
P. W. Bridgman	H. D. Harradon	F. R. Moulton
W. H. Bucher	N. H. Heck	A. K. Snelgrove
W. B. Cannon	J. B. Macelwane	H. T. Stetson
E. G. Conklin	J. P. Marble	W. T. Thom, Jr.
E. DeGolyer	K. F. Mather	T. G. Thompson
L. P. Eisenhart	O. E. Meinzer	F. E. Wright

During the past year the Chairman of your Committee has been necessarily concerned with the functions of the Division of Foreign Relations of the National Research Council (NRC). He, therefore, presents for publication in the Transactions a digest of "A memorandum on the activities and future plans of International scientific organizations, 1919-44: Relation of science to postwar planning." This Memorandum includes the reports and opinions of all the available officers (1944) of International scientific organizations, particularly the officers or adjutants of International Scientific Unions and Congresses. Many other authorities on science, education, and International affairs have contributed to the preparation and editing of the Memorandum, which is signed by Dr. WALTER B. CANNON, as Chairman of the Division of Foreign Relations of NRC and Foreign Secretary of the National Academy of Sciences (NAS), and RICHARD M. FIELD, American Representative, Committee on Science and Its Social Relations of the International Council of Scientific Unions (ICSU), Division of Foreign Relations of NRC.

Abstract of Memorandum

The original Memorandum of 49 typewritten pages is outlined as follows:

Part (I)--Introduction; reasons and authority for the Memorandum, including the methods used in obtaining the essential data; type of questionnaire
(II)--Source and area of information
(III)--Digest of replies
(IV)--Summary of majority and minority opinion
(V)--Conclusions and recommendations

Appendix A--List of contributing personnel
B--List of officers of International scientific organizations: (1) Active; (2) inactive; (3) unavailable; (4) deceased; (5) adjutants
C--Documented information
D--Test-cases as examples in International scientific cooperation in fundamental science (non-war) for the periods 1919-29 and 1529-44
E--List of expatriate or displaced foreign scientists in the United States (classified according to profession and nationality)

Only Parts I, II, IV, and V of the Memorandum are quoted in this Report, together with those items in Part III which specifically refer to the affairs of the International Union of Geodesy and Geophysics (IUGG), its Associations and Commissions. A printed edition of the full Memorandum, together with subsequent comments, will be published later in an International journal.

PART I--INTRODUCTION

"In 1813, when France and England were fighting each other, Sir Humphrey Davy visited Paris, was awarded a gold medal by the Academie des Sciences, and elected a corresponding member. Such amenities have long since vanished" (from Report of the Division of Foreign Relations, NRC, 1943).

This Memorandum has been prepared for the Division of Foreign Relations of NRC. Copies have been requested by the Division of International Conferences of the United States Department of State, by non-American officers of the "Unions", and by other agencies concerned with the International aspects of science, technology, and their social relations, including the ICSU and the Royal Society of Great Britain. This Memorandum will not attempt to define science, or scientific method, except in terms of the seven existing technical divisions of the NRC of the United States, and the interrelation of their problems with those of the Division of Foreign Relations. These seven technical divisions of the NRC are: Division of Physical Sciences; Division of Engineering

and Industrial Research; Division of Chemistry and Chemical Technology; Division of Geology and Geography; Division of Medical Sciences; Division of Biology and Agriculture; and Division of Anthropology and Psychology. If economics and politics are not recognized in this Memorandum as sciences, it is because they are not so recognized by the NRC of the United States nor by any National Committee of any International Scientific Union. The implications, however, of the responsibilities of scientists to society are suggested not only in the general organization of the NRC, but also by the American representative of the Committee on Science and Its Social Relations of the ICSU. It should also be noted that American officers of International Scientific Unions represent their Unions in the Division of Foreign Relations. The ultimate authority for the preparation of this Memorandum is through the Division of Foreign Relations of the NRC of the United States according to paragraphs 3, 4, and 6 of Executive Order No. 2859, May 11, 1918.

This Memorandum is in no way directly connected with science and the winning of the war; it is, however, concerned with science and the winning of the peace. For quite obvious reasons no truly International organization has been, or ever could be, created for winning wars. We are not aware of the full degree of Axis effort and efficiency in scientific cooperation for winning the war. We are aware of our own National scientific organizations and British organizations, including their cooperation, for the same purpose. The Division of Foreign Relations of the NRC is particularly concerned, because of its full responsibilities in any and all scientific and technological contributions to winning and maintaining a reasonable comity among Nations, including the about-to-be liberated areas and those of their defeated invaders.

War is a great stimulus to National, and to limited International, cooperative scientific research in most, if not all, of the applied sciences. On the other hand, this stimulus though greatly increasing scientific effort necessarily has uneconomic, unsocial, and inhumane implications. It is only in times of relative peace between Nations that the fundamental and cumulative effects of the impact of science and technology on human society can be studied by the scientific method, without interference of ideological propaganda and wishful thinking associated with war-time economics and war-time politics. Similar, though less intense, restrictions interfere even in times of peace with the complete interchange of scientific techniques for the benefit of the people of all Nations. These restrictions, therefore, also tend to interfere in all International scientific and technological gatherings, particularly when the scientific personnel act primarily as delegates of their National institutions rather than as scientists representative of their countrymen. Only continuous effort will accelerate International cooperation in fundamental science, or in scientific research beneficial to all men, and inimical to none.

This Memorandum is, therefore, concerned with the continuity of International cooperative research, and particularly with the accomplishments of International scientific organizations during the rise and fall of the Treaty of Versailles and its geopolitical implement, the League of Nations. It is significant that during this period, 1918-39, excellent machinery was developed for the comity of Nations through science. This machinery was sponsored by 42 Nations, including all the present belligerents, neutrals, and invaded countries with the exception of Russia and, at times, of Italy. It should be further noted that at no time were the scientific representatives of the United States in any way seriously embarrassed in their deliberations or responsibilities by the fact that their country had helped to plan the League of Nations but refused to join it.

JOSEPH NEEDHAM has recently written a Memorandum on an International Science Cooperation Service in which, after stating that "various science cooperation offices which have already been set up under the stress of war in the capitals of the United Nations constitute a piece of machinery too precious to be allowed to disappear after the war", proposes that this "existing or nascent machinery" be transmuted into an "International Science Cooperative Service whose representatives in all lands would have diplomatic status (or whatever status was accorded formerly to officials of the League) and full Governmental facilities in communication and transportation, but who would be drawn from both Government and academic laboratories, and hence would be free from commercial entanglements." It should be noted that JOSEPH NEEDHAM makes no mention of the International Scientific Unions and does not explain why Government and academic representatives are necessarily "free from commercial (therefore political) entanglements."

The question may be posed as to the advisability of the scientists of the world experimenting with International organizations, or participating in International scientific meetings which are not initiated by one or more Governments, but by the scientists themselves.

The Russian Government is the only great power which appears to have carefully considered the importance of this question.

The least sporadic and opportunist of International scientific organizations have been the Congresses and Unions; of the two, the Congresses are the older. The history of International Congresses, Committees, and other forms of organized International cooperation goes back to the second part of the last century. It is essential that those scientists who are today (either independently or as advisers to their Governments) planning postwar research and education become familiar with previous efforts in their field and related fields. They should do this in order that they may evaluate the past experience of others before attempting to define the framework of new or duplicating organizations.

Certain departments of science and technology are represented by the Congresses, and others by the Unions; but some departments of science are represented by both Congresses and Unions. For instance, in the case of the biological sciences, the Union and the Congress are closely related; in the case of the earth-sciences, the IUGG overlaps particularly the functions of the International Geological Congress (IGC); but there has been no particular liaison between these International organizations either as to agenda or meetings, except through a Commission of the IUGG.

The scientific Congresses do not function between meetings, and, at times, are more subject to political opportunism, as in the case of the last or Eighth American Scientific Congress. The mechanism of the International Scientific Unions includes Bureaus which are expected to function continuously between meetings; and the Unions are financed by all countries which adhere to one, or more, of them. The control of each Union, however, is through its Bureau, whose officers are elected at a General International Assembly. Each International Scientific Union also has its National Committees which represent the affairs of each Union on a National Research Council, National Academy, National Society, or analogous National Scientific Council. Finally, there is an ICSU whose primary function is the coordination of all science particularly for the promotion of International friendship through competitive but sympathetic cooperation. The last report (1939) of the ICSU was through its Committee on Science and Its Social Relations. This report consists of the original data supplied by each National representative of the ICSU. Unfortunately, the United States never submitted its report. Of particular significance at the present time (1944) are the reports from Poland, Estonia, Latvia, Canada, and Great Britain.

This digest of the organizations, methods, and activities of the International Scientific Unions is predicated on the assumption that any adverse criticism is probably equally, if not more, applicable to other existing National and quasi-International organizations.

Dependent upon the character, rather than upon the profession, of their officers, certain of the International Unions have been more effective than others. On the whole, however, the activities of the International Scientific Unions from 1918 to 1944 warrant the recent statement by an executive officer of one of America's leading technical, social, and philanthropic organizations: "If there is any nucleus of International goodwill and understanding left in the world, it resides, I think, in scientific personnel. They will be the first to mend the broken wires of communication, and I hope this time all the world will realize, whether we like it or not, we have to live together on a globe which science has made too small for war" (July 11, 1944).

At the April (1943) meeting of the Executive Committee of the Division of Foreign Relations, there was some discussion of the war-time activities of the International Scientific Unions. This discussion was precipitated by the difference in the reports of the American officers and their adjutants. The relative activity or inactivity of each American officer did not seem to be conditioned entirely by the department of science which his Union represented nor by the fact that he and his colleagues were particularly burdened by their contributions to the war-effort. After some informal discussion it was decided to circularize all available officers, or adjutants, of the International Scientific Unions and International Scientific Congresses. This was done in the form of a questionnaire which was finally formulated by three members of the Executive Committee, Division of Foreign Relations, NRC, and jointly transmitted by the Chairman of the Division of Foreign Relations and the NRC Representative of the Committee on Science and Its Social Relations, ICSU. This questionnaire was issued during the last week in March, 1944, and is given below.

Questionnaire--(1) To what extent has there been interchange of information in your field between your country and foreign countries, other than for war-purposes, during the past two years? By: (1) Officers and personnel of your International Scientific Union (Congress); (2) National societies; (3) National educational and research organizations; (4) personal correspondence.

(II) Are members of your Union (Congress) planning an International meeting as soon as world conditions will permit? (1) If so: Why and where? (2) If not: Why not?

(III) If your Union (Congress) through its National Committees or Commissions is still active, do your activities include: (1) Interim reports; (2) preparation for resumption of your International Journal or Transactions; (3) continued Government financing through one, or more, of the National Committees; (4) plans for International interchange of technical publications with the allied and neutral countries. Also, plans for interchange with Axis-occupied countries after the war.

(IV) Have the officers of your Union (Congress) kept in touch with the officers and personnel of other Unions (Congresses)? If so, with which countries, and what was the nature or general purpose of the correspondence?

(V) Are there specific scientific projects, requiring International cooperation, in which your Union (Congress) could participate, with essentially equal advantage to all cooperating countries?

(VI) Does your experience lead you to believe that postwar International cooperation in science and education could best be served by other organizations than International Scientific Unions or Congresses? If so, why?

PART II--SCOPE AND AREA OF THE REPLIES TO THE QUESTIONNAIRE

The answers to the questionnaire, to date, are documented in Appendix C (not included in this summary of the Report).

(I) International Union of Pure and Applied Physics (IUPAP)--According to letter (April 25, 1944) from L. P. EISENHART, Chairman, Division of Physical Sciences, NRC, and Representative, American Section of the Union, Division of Foreign Relations, NRC: "No International activities of the 'Union' to report." The latest information regarding the activities of the Bureau is contained in a letter (October 3, 1941) from M. SIEGBAHN to the Executive Secretary, NRC. The following international scientific organizations may be classified with (related to) applied physics or engineering:

(A) International Bureau of Weights and Measures (IBWM)--According to L. J. BRIGGS, Representative, American Section IBWM; also some information which, for political reasons, can not be quoted.
(B) International Electrotechnical Commission (IEC) and International Commission on Illumination (ICI)--According to E. C. CRITTENDEN, Representative, American National Committee IEC and ICI.
(C) International Scientific Radio Union (ISRU)--According to J. H. DELLINGER, Chairman, American Section, ISRU; also further information by others, marked "restricted" and, therefore, may not be quoted for war-reasons.
(D) International Mathematical Congress (IMC)--According to R. G. D. RICHARDSON, Secretary.

(II) International Union of Chemistry (IUC)--According to M. T. BOGERT, President.

(III) International Union of Biological Sciences (IUBC)--According to E. D. MERRIL, President; also related:

(A) International Paleontological Union (IPU)--According to B. F. HOWELL, Secretary; also E. DORF, Chairman, Committee on Paleobotany, NRC.
(B) Botanical Section (IUBS)--According to F. VERDOORN, Honorary Secretary.
(C) International Medical Organizations (IMO)--According to W. B. CANNON, Chairman, Division of Foreign Relations, NRC, and Foreign Secretary, NAS.
(D) International Aspects of Horticulture (IAH)--According to proposed American Horticultural Union, E. L. D. SEYMOUR, Secretary.

(IV) International Geographical Union (IGU)--According to C. F. ARDEN-CLOSE, First Vice-President, IGU; also J. K. WRIGHT, Chairman, United States National Committee, IGU.

(V) International Geological Congress (IGC)--There is no International Geological Union. According to W. F. T. McLINTOCK, General Secretary, IGC, and R. M. FIELD, Foreign Correspondent, Geological Society of London.

(VI) International Union of Geodesy and Geophysics (IUGG)--According to H. ST. J. WINTERBOTHAM, General Secretary, IUGG; J. A. FLEMING, Vice-President, IUGG, and General Secre-

tary, American Section, IUGG; also N. J. OGILVIE, Canadian National Committee, IUGG, and R. M. FIELD, Chairman, Commission on Continental and Oceanic Structure, IUGG. Also related:

(A) International Association of Geodesy (IAG)--According to W. D. LAMBERT, American Representative, and Acting President, IAG.
(B) International Association of Seismology (IAS)--According to N. H. HECK, President, IAS, and J. B. MACELWANE, Chairman, American National Committee, Pacific Seismology.
(C) International Association of Meteorology (IAM)--According to S. CHAPMAN, President, IAM.
(D) International Association of Terrestrial Magnetism and Electricity (IATME)--According to J. A. FLEMING, President, and S. CHAPMAN, Vice-President, IATME.
(E) International Association of Oceanography (IAO)--According to P. C. WHITNEY and T. G. THOMPSON, Representatives, Division of Foreign Relations, NRC; see also Commission on Continental and Oceanic Structure, IUGG.
(F) International Association of Volcanology (IAV)--According to T. A. JAGGAR, Vice-President, and J. E. RICHEY, Emergency President, IAV; see also Commission on Continental and Oceanic Structure, IUGG.
(G) International Association of Scientific Hydrology (IASH)--According to O. LÜTSCHG, President, IASH (O. E. MEINZER, United States Representative).
(H) International Commission on Snow and Glaciers (ICSG)--According to J. E. CHURCH, President, ICSG.
(I) International Commission on Subterranean Water (ICSW)--According to O. E. MEINZER, President, ICSW.
(J) International Commission on Continental and Oceanic Structure (ICCOS)--According to R. M. FIELD, President, and J. A. FLEMING, Secretary, ICCOS.

(VII) International Astronomical Union (IAU)--According to A. EDDINGTON, President, and W. S. ADAMS, Secretary, IAU, and J. STEBBINS, Chairman, American Section, IAU; also B. J. BOK, Chairman, Committee on Distribution Astronomical Literature.

(VIII) International Congress of Psychology (ICP)--Psychology has no International Union. According to H. S. LANGFELD, Secretaire Adjoint, ICP.

(IX) Eighth American Scientific Congress (1939)--Congress of 21 American Republics. Review as of 1944, according to A. WETMORE, Secretary of Congress, and W. KELCHNER, Chief, Division of International Conferences, United States Department of State.

(A) Section on Physical and Chemical Sciences (SPCS)--According to L. J. BRIGGS, Chairman, SPCS, but information is "restricted".
(B) Section on Geological Sciences (SGS)--According to T. W. VAUGHAN, Chairman, SGS.
(C) Section on Public Health and Medicine (SPHM)--According to T. PARRAN, Chairman, SPHM.
(D) Section on International Scientific Exchange (SISE)--C. H. HARING, Chairman, SISE.
(E) Section on Economics and Sociology (SES)--H. G. MOULTON, Chairman, SES.
(F) Section on Agriculture and Conservation (SAC)--H. H. BENNET, Chairman, SAC.
(G) Section on Biological Sciences (SBS)--E. G. CONKLIN, Chairman, SBS.
(H) Section on History and Geography (SHG)--According to P. E. JAMES, Chairman, SHG.
(I) Section on Anthropological Sciences (SAS)--According to H. J. SPINDEN, Chairman, SAS.
(J) Section on International Law and Jurisprudence (SILJ)--G. A. FINCH, Secretary, SILJ.
(K) Section on Education (SE)--According to N. M. BUTLER, Chairman, SE.

(X) International Scientific Organizations--According to W. G. LELAND, Chairman, Advisory Committee on Cultural Relations, United States Department of State.

(XI) International Conferences on Intellectual Cooperation, Havana (1941)--A. RAESTAD and A. V. HILL, Secretary, Royal Society of London.

(XII) International Publications--By F. VERDOORN, Honorary Secretary, Botanical Section of the International Union of the Biological Sciences.

PART III--REPORT ON ITEM VI, PART II, ONLY

International Union of Geodesy and Geophysics

Geodesy and geophysics are represented on the NRC of United States by the Executive Committee of the American Geophysical Union (AGU). The Executive Committee of the AGU also includes the Chairmen of the five Divisions of NRC, (1) Foreign Relations, (2) Physical Sciences, (3) Chemistry and Chemical Technology, (4) Geology and Geography, and (5) Biology and Agriculture.

(I) Officers and personnel of the Union have interchanged information with foreign countries, other than for war-purposes, during the past two years, especially with Great Britain and Canada.

(II) The Eighth International Assembly was to have been held in 1942 in Norway. According to a letter (November 23, 1943) from the Norwegian Embassy, Washington, D. C.: "The Ministry of Education and Ecclesiastical Affairs considers the invitation to be still in force and regards it as a great honor for Norway to be host for the next meeting of your Union, in which so many Norwegian scientists have taken an active part."

(III) Informal interim reports are maintained through National Committees (see also ICCOS). The Union has maintained contacts with the other Unions, notably the IAU and the ICSU during the war-period. Triennial and other publications will be resumed after the war, and copies of the Transactions of 1939 are reserved for distribution to all adhering Nations at the earliest opportunity. The Union continues to receive dues, because of adherence, from the United States Government, and from the British Government. The bulk of the Union's funds are banked in Great Britain and in the United States. The Union, during the war, has financed several projects.

(IV) See reports from the Associations and Commissions (pp. 354-358).

(V) A large number of projects in which the Union cooperates and should continue to cooperate, with equal advantage to all countries.

(VI) Postwar International cooperation in science and education could not be better served by other organizations than by International Scientific Unions. Of the 32 countries which adhere to this Union, three are Axis-enemies, 14 are in the hands of the enemy, four are neutrals with whom no contact is allowed, four are British, and seven are in the Americas. The particular value of a Union, rather than a Congress, is that a Union provides (1) continuity of touch in administration and finance, (2) power of instituting, at once, some much-needed practical collaboration, with a minimum of institutional or National politics (March, 1944).

(a) International Association of Geodesy (IAG)

(I) Frequent contact has been maintained by correspondence between American officers of the IAG with accessible officers of that organization and of the IUGG in other countries. The National society (or nearest corresponding organization) for geodesy in the United States of America is the Section of Geodesy of the AGU. There has been contact by correspondence between its officers and members and geodesists in other countries. Some of the work done by the United States Coast and Geodetic Survey is "restricted" or "confidential" during the war. No other information is available. Considerable attention has been given to promoting an interest in geodesy and to the initiation of actual geodetic work in Latin America. Some of the Latin American countries have been nominal members of the IUGG and therefore of the IAG but have taken almost no part in its affairs. It is hoped that after the war all Latin American countries will participate actively in the work of the IAG.

(II) It is planned to hold a meeting of the IUGG and of its branch, the IAG, at Bergen, Norway, as soon as conditions will permit. The invitation for the Bergen Assembly was given and accepted at the Assembly of 1939 in Washington, D. C.

(III) War-conditions prevented the publication of much of the material that would normally have been published in connection with the meeting of 1939 of the IAG. The publication of two reports of the IAG, which would otherwise have gone unpublished, was undertaken by the United States Coast and Geodetic Survey, and the AGU sponsored and financed the publication of a pamphlet containing the proceedings of the meeting of 1939 at Washington. These proceedings would normally have been published in the Bulletin géodésique, official organ of the IAG, publication of which was interrupted by the war. The correspondence already referred to dealt in part with the resumption of publication of various sorts. The IUGG, of which the IAG is a branch, has continued to receive from the State Department money for the annual dues for adherence of the United States of America.

(IV) Contact particularly with the IAU, especially in connection with the work of the International Latitude Service, which receives support both from the IAU and the IAG (compare this statement with that of the IAU).

(V) In geodesy alone there are the International Latitude Service (Central Office at Naples), the Bureau international de l'Heure (Central Office in Paris), and the Isostatic Reduction Office

(Central Office at Helsinki). "The International Bibliography of Geodesy is issued triennially, but only two volumes have appeared and not enough copies are available. This Bibliography covers in principle all European languages and includes non-critical abstracts of the books and articles listed. It is extremely useful and deserves international support because the income received from subscribers and purchasers of copies will not suffice to maintain it" (W. D. LAMBERT, September 7, 1944). Some means should be found to assure the continuance of these offices.

The IAG also has triennial reports made by designated reporters on various branches of the subject. These should be of general interest to adhering countries, though not necessarily, of course, equally so to all of them.

(VI) "Something very like the Unions is needed in my opinion. Congresses do not ensure the necessary continuity nor provide for the support of continuing projects, such as are mentioned under (V). Congresses do, however, make possible a wider participation by interested persons. There is always the possibility that the Unions, with their attendance limited to official delegates, may get into the hands of a self-perpetuating clique.

"Perhaps the Unions might sponsor Congresses with fewer restrictions on the attendance of delegates, or provision might be made for larger and possibly more representative delegations to the ordinary Union meetings. These meetings, however, could easily become too large for the convenient transaction of necessary business, in which case such business would probably be railroaded through by a small cohesive group.

"There seems to be no ideal solution" (W. D. LAMBERT, September 4, 1944).

(b) International Association of Seismology (IAS)

(I) Considerable correspondence has been carried on with available officers of both the Association and the Union during the war. Appointment has been made to replace the deceased Vice-President. Contact was maintained with National societies and their International operations. Personal correspondence and informal conferences regarding postwar plans were maintained. "Dr. ROBERT STONELY of Cambridge University (England) has accepted appointment as Acting Vice-President of the Association to replace F. J. WHIPPLE (deceased). On the assumption that central France may soon be liberated I have informed Acting Vice-President STONELY of my views as to what ought to be done about the Central Bureau of the IAS" (N. H. HECK, August 12, 1944).

(II) See Item II of Section on IUGG.

(III) Interim reports have been made, particularly to the NRC and to allied American organizations, including Government agencies. Together with ICCOS, the Association has helped finance continuity of seismograph stations in Greenland and Bermuda.

(IV) The Association has kept in touch with all available officers, or their alternates, of the other International associations.

(V) Seismology is essentially an International subject which requires complete interchange of instrumental records, and the careful consideration of the best location of seismographs in all parts of the world.

(VI) Since the Association survived the last war, and has shown considerable vitality during this one, its continuance is particularly warranted.

(c) International Association of Meteorology (IAM)

(I) No direct interchange of information has gone on during the war through officers of this Association except between England the United States of America. Science abstracts have been helpful. Also wireless abstracts and occasional scientific reprints are received from colleagues in Sweden and Switzerland. There has been no direct scientific contact with Russia.

(II) Preparations should be started for an International Meeting of the Executive Committees of the Union and their Associations, with, possibly, addition of other scientists personally invited.

(III) The Royal Society is considering the whole future of International organizations of science, with Special Committees considering future needs of the various branches of geophysics, including a review of Governmental help, regarded as necessary.

(IV) See Item (I).

(V) There are a number of international projects in which the Association should participate to a much larger extent than before the war.

(VI) Renewal and improvement of the Union and its Associations are most important for the progress of science, especially astronomy and geophysics. Activities can be most usefully extended, but methods to be adopted will need careful consideration to avoid some of the jealousies and inefficiency in the prewar Unions.

(d) International Association of Terrestrial Magnetism and Electricity (IATME)

(I) Informal interim reports have been continued since 1929 through several Committees and Commissions. Continuance of magnetic character-figures has been maintained with the cooperation of the Carnegie Institution of Washington.

(II) See Item (II) of Section on IUGG.

(III) See Item (I).

(IV) Important fundamental problems, the solution of which requires the continuous International cooperation of geomagnetism, meteorology, and volcanism, are being carefully considered.

(V) A number of specific projects require the help of the other Associations because of essential International continuity of instrumental surveys and interchange of observations and records, such as: Maintenance of magnetic character-figures; reduction of magnetic observations of isomagnetic charts; etc. See also report of ICCOS (p. 358).

(VI) The Association, because of its contacts, experience, and interests, is particularly prepared for cooperation with other International agencies in postwar science and education. This is particularly true in the case of oceanographic magnetic surveys, both for fundamental and practical reasons.

(e) International Association of Oceanography (IAO)

For sub-oceanic geomorphology and geology, see report of ICCOS.

(I) No comments.

(II) The National Committee appreciates the economic and political aspects of scientific oceanography.

(III) No comments.

(IV) The National Committee is particularly interested in planning a vigorous program of research in the Pacific Ocean, and will need the cooperation of the Association.

(f) International Association of Volcanology (IAV)

No report has been received, but a statement by its Vice-President in the United States (August 8, 1943) is as follows: "I do not believe in International organizations but in individuals . . . . . Volcanological research should be entirely local and institutional." See also statement of the ICCOS (p. 358). In contradistinction it is reported from London that "as no communication has been, or is, possible between the President of the Association, Professor MICHEL-LEVY, and the world outside the conflict, the Secretary-General, Brigadier WINTERBOTHAM, has appointed J. E. RICHEY as an Emergency President to act for Professor MICHEL-LEVY."

(g) International Association of Scientific Hydrology (IASH)

(I) Since 1939 there has been limited correspondence among the officers of the Association.

(II) The work of the Association has been done chiefly through the agency of several International Commissions, the principal ones being the Commissions on Potamatology, Limnology, Subterranean Water, and Snow and Glaciers. All of these Commissions have European Presidents except the Commission on Snow and Glaciers and the Commission on Subterranean Water. See separate report by J. E. CHURCH, President, Commission on Snow and Glaciers and O. E. MEINZER, President, Commission on Subterranean Water.

(III) The Vice-President of the Association was present at the last meeting of the IUGG in Washington (1939). The Secretary of the Association arrived but left immediately on account of the war. F. E. MATTHES served as Temporary Chairman for the Washington Meeting, but the Proceedings have not yet been published.

(IV) See Items (I) and (II).

(V) See reports of Commissions on Subterranean Water and on Snow and Glaciers.

(VI) "The next meeting of the IASH will, of course, be determined by the decisions that are made in regard to the next meeting of the IUGG, of which it is a part. It seems to me that it is too early to make decisions in regard to such a meeting, but I am heartily in favor of holding a meeting as soon after the war as may be practicable. It would certainly be fine if the meeting could be held in Norway, as was voted at the Washington Assembly (1939), but I appreciate that our plans will have to be adapted to the conditions that will exist at the close of the war" (O. E. MEINZER, August 26, 1944).

(h) International Commission on Snow and Glaciers (ICSG)

(I) There has been some correspondence, since 1939, with Russia, Switzerland, England, Australia, and New Zealand.

(II) The plan is to meet with the IUGG at Oslo or Bergen, Norway, to catch up on the program for 1942, wrecked by the war.

(III) As a result of the war, substitute officers were temporarily selected, for those in occupied countries, to carry on the business of the Association, in order to restart full International activity at the very first possible moment.

(1) No interim reports.
(2) Resumption of an International Journal or Transactions.
(3) Reprints have been stored for distribution to all countries as soon as possible.

(IV) There has been interchange of opinions, particularly during the war, with GERALD SELIGMAN (England) and OTTO LÜTSCHG, President of the Association (Switzerland).

(V) Numerous projects require International cooperation for the benefit of all countries. We are, therefore, not waiting for the war to end in order "to reawaken scientifically to the melancholy waste of time in destroying what has been so laboriously built up" (J. E. CHURCH, August 28, 1944).

(VI) See Item (II). Also "The IASH deserves specific commendation because of the breadth of view and sturdy leadership of its past President, SMETNA, and President LÜTSCHG. Its Executive Committee even on the eve of the outbreak of hostilities was represented in a meeting in Germany by most of the countries of Europe and showed a remarkable unanimity of policy and loyal support of President LÜTSCHG as against the ultra-conservative attitude of our French Secretary DIENERT" (J. E. CHURCH, August 28, 1944).

(i) International Commission on Subterranean Water (ICSW)

(I) There has been correspondence with the President and Vice-President of the IASH; also with the President of the ICSG. There has also been some correspondence with members of the Commission, in different parts of the world, during the war. The principal activity of the Commission, during the war, has been in the Western Hemisphere with the members and advisory members from the Latin American countries. This activity has been aided by the cooperation of the United States Geological Survey, the Pan-American Union, and the Office of the Coordinator of Inter-American Affairs. This has been accomplished in spite of the pressure of war-work (see Trans. Amer. Geophys. Union for 1943 and 1944).

(II) See Item (II) of Section on IUGG.

(III) See Item (I).

(IV) Only through the Central Bureau of the IASH [see Item (I)].

(V) Not mentioned specifically, but implied.

(VI) Not mentioned specifically, but implied.

(j) International Commission on Continental and Oceanic Structure (ICCOS)

This central organization was created by the IUGG during the Seventh General Assembly at Edinburgh in 1936. Its primary function is to promote the use of geophysical methods in the solution of the structural problems of suboceanic and continental areas, with the essential cooperation of geologists and their National and International organizations.

(I) There has been interchange of information with all available officers of the IUGG, both in the United States of America and other countries during the war, and also with such National societies as the American Institute of Mining Engineers, the American Association of Petroleum Geologists, the American Physical Society, the American Institute of Physics, the Geological Society of America, the Geological Society of London, and numerous educational and research institutions.

(II) A report is planned for the next meeting of the IUGG.

(III) The Commission has contributed to several interim reports (1939-44), including those of the Division of Foreign Relations, NRC. Its last interim report was published in April, 1943, and it has material already prepared for the resumption of the Transactions of the IUGG. The work of the Commission is still maintained by funds from the IUGG.

(IV) The Commission has maintained continuous communication with the American (United States, Canada, and Mexico) officers of the IUGG, also with the officers of the IGC, and the American representatives of related International organizations, that is, physics, engineering, chemistry, meteorology, geophysics, and, when necessary, with the United States Department of State and the Washington Embassies of the Netherlands, Norway, and Finland.

(V) International projects which have been sponsored by the Commission are: (1) Gravimetric and suboceanic topographic surveys of the Gulf Caribbean Region and the English Channel, requiring the cooperation of the IAG, the British and American Navies, the United States Coast and Geodetic Survey, the American Bell Telephone Laboratories, the Royal Society of Great Britain, Cambridge University (England), Lehigh University (United States of America), Princeton University (United States of America), the NRC of the United States, the AGU, and other private National institutions and agencies. (2) Initiated suboceanic seismic exploration of the Atlantic Ocean with the cooperation of the IATME, the United States Geological Survey, the Geological Society of America, the Woods Hole Oceanographic Institution, the NRC, the Guggenheim Foundation, the Geological Society of London, the Royal Society of London, and other private and National institutions and business corporations. (3) Cooperation with the IAS in the maintenance of seismographic stations in Bermuda, Greenland, and Latin American countries. (4) Cooperation in the tabulation and publication of International data, or data of International significance.

The Commission has particularly stressed the need for further cooperation of numerous agencies in the solution of fundamental problems in geoscience, both within and without the IUGG. Examples: (1) Geographic coordinates in relation to problems in structural geology. (2) Plans for joint British-American survey of the mid-Atlantic Ridge. (3) Continuation of geophysical-geological exploration of island-arcs as essential to better understanding of mountain building and geosynclines. (4) Study of earthquake-velocities and isoporic foci with special reference to differences in the continental and suboceanic lithosphere. (5) The geophysical, as well as the geochemical, study of volcanoes as an indication of subcrustal conditions. (6) Configuration of the Pre-Cambrian basement. (7) Cosmic-terrestrial relationships. (8) Contributions to the methods for improving International cooperation in science and its social implications.

(VI) In spite of the war the Commission has been able to prepare for its postwar responsibilities by maintaining correspondence and informal conferences with the available officers of the Associations of the IUGG, including its General Secretary. It has further maintained its interim efficiency by the appointment of alternates for Axis, and for Axis-occupied countries, until such time as the scientists of these countries are able to resume their proper responsibilities. As an active implement of the IUGG, the Commission considers that all International Scientific Unions have exceptional opportunities for the increase of comity among Nations through International cooperation in fundamental science.

PART IV--SUMMARY OF MAJORITY AND MINORITY OPINIONS

(I) Participation of scientists and technological experts in organized International conferences may be classified as follows:

(A) As expert advisers (consultants) to their respective Governments, either as heads or delegates of Government Bureaus, or as individuals recommended or selected from the personnel of private organizations, such as universities and industrial corporations.

(B) As members of Bureaus or Commissions organized by their respective Governments, and largely, if not entirely, composed of Government employees.

(C) As representatives in Congresses which are, or are not, preponderant in Government personnel. It is peculiar to Congresses that they have little or no continuity between meetings, which occur every three or four years.

(D) As delegates of National Academies, National societies, and National research and educational institutions. Such International meetings are claimed to be less influenced by geopolitics, but they are the most sporadic, and depend entirely (to date) in most countries on private (philanthropic) financing. It is only in the case of classes (A) and (B) that the delegates are not expected to pay most, if not all, of their own expenses. It should be further noted that (A) and (B) illustrate the organization of scientists--partly, if not mainly--for economic and political (geopolitical) reasons, while (C) may be "border-line"; in this respect, (D) is primarily "International-academic". There are certain practical differences between the Russian Academy of Sciences, the Royal Society of Great Britain, and the NAS of the United States. The Russian Academy of Sciences is directly responsible to its Government; but so is the Royal Society to its Government in terms of directives and their implementation. The NAS of the United States has never accepted the same economic and political responsibilities in the same way as has the Royal Society. It should also be added that certain criticisms by American scientists of the lack of academic freedom of Russian scientists is incorrect, and largely founded upon the opinions expressed by some officers of some American scientific organizations. It is, perhaps, for this reason that recently the Russian Government, through its Academy, has preferred to communicate with individual American scientists rather than with their organizations.

(E) As Unions (International Scientific Unions), which combined many of the best (most constructive) features in (A), (B), (C), and (D), with important additional features such as: (1) Continuity of responsibilities, effort, and finance; (2) a minimum of political and economic control by Government agencies.

(II) The following digest is primarily in terms of the opinions of scientists who have participated in one or more of the types of International conferences listed as (A) to (E), and secondarily, according to their technical aptitudes. It should be noted, however, that with very few exceptions this is a digest of North American (United States, Canadian) and British Commonwealth opinions, that is, the opinions of the English-speaking scientists, and of their institutions. The reasons for the lack of available Latin American opinions are stated in Part III of this Memorandum (not reprinted here) together with the necessity for the opinions of other Nations, notably the Netherlands, Switzerland, and the Finno-Scandinavian countries. Turkey and Russia exhibit a significant hiatus; and Germany, Italy, and France require immediate consideration in any postwar agenda and program on science and its social relations in western Europe. The same is true for Japan and China in Asia.

(III) Digest--The majority opinion of the available, responsible officers of International Scientific Organizations is that they are an essential implement to the progress and comity of Nations. This is all the more significant because the roster includes scientists in the employ of both private and Government organizations. But it should be noted that this majority opinion is largely due to geoscientists and to astronomers; an important exception are the geographers. In the case of mathematics it would appear that the leaders are somewhat asocial both in research and education, and have a tendency to National hibernation--in the scholarly sense--during periods of International conflict. This may be, in part, because research in fundamental mathematics is largely independent of travel and related observation even in times of world peace, when it is both helpful and pleasant to associate with, and honor, one's colleagues. There are some notable exceptions to this temporary analysis, but principally in the field of applied mathematics, as particularly exemplified by engineering, geophysics, and economics. Perhaps the mathematicians and astronomers best illustrate the aphorism of Dr. BRUZS of Latvia in his report of 1938 to the Committee on Science and Its Social Relations of the ICSU: "I distinguish two elements in science, its utility and its intellectual charm."

Because chemistry and physics are fundamental techniques to all the other natural sciences they are, par excellence, examples of the interrelation of science and society through their economic application, particularly in medicine and in manufacture. It is therefore of some interest

to note and compare the reports of the American officers, and their adjutants, of the International Organizations of Chemistry and Physics. According to the preceding introduction, the summary of the available data may be summarized as follows:

The majority opinion of the responding, responsible officers of the International Scientific Unions is:

(1) The Scientific Unions, in view of their past experience and accomplishments (1919-1944), are the most efficient existing International organizations both in promoting fundamental science and in implementing the relation of science to human affairs. The principal defects in the past history of the Unions which may be rectified by amendments to their charters are: (a) Political jealousies arising from National pride; (b) over-emphasis of delegates of National institutions rather than of the science which the institutions represent; (c) National economic rivalry in the allocation of International funds; and (d) indifference and consequent inefficiency of National Committees. However, it has been demonstrated by those Unions whose officers have accepted their responsibilities (1919-1944) that the self-criticisms listed have not seriously interfered with the fundamental directives or continuity of the Unions; and, as well recognized, human phenomena are by no means peculiar to scientific organizations.

(2) International Congresses, which have been primarily organized for National or geo-political purposes, have been neither economical of the public funds nor efficient in the expenditure of the scientists' time and energy. One reason why this has not been more fully appreciated by the public and their Governmental representatives is not so much the technical difficulties of science as to the fact that Government scientists who participate in such Congresses may not express their personal opinions on the efficiency of International meetings organized by their Government. Furthermore, most non-Government-employed scientists do not wish to discuss such matters as a scientific problem; those who do discuss them usually do so in relation to "academic freedom", "political control", "unscientific methods", and "emotionalism", which they attribute to either the legislative or the executive (or both) branches of their Government. This appears to be particularly the case in the United States, regardless of whether the critics are academicians or employed by commercial organizations. In the case of those Congresses which are primarily organized by the scientists themselves, the principal self-criticism seems to be lack of continuity in International cooperation between meetings. Many scientists, however, feel that is a good thing because it prohibits the growth of purely political motives, while encouraging the further development of personal and group contacts as the desire for such cooperation develops naturally with the progress and consequent changes in scientific problems and techniques. Another difficulty is the lack of funds, except as raised by the National Committee for the expenses of the Congress in the country where it is held. This also is deemed an advantage by some scientists as it precludes any of the responsibilities connected with the administration of International funds.

(3) International Scientific Conferences organized by National private organizations--There is a strong preference among certain British and American scientists for this form of International cooperation, particularly in fundamental science. This preference, however, seems to be principally confined to scientists of the colleges and universities, and especially those who have been elected to our most honored and most selective National Academies and National societies. Other scientists, however, have noted that such International Conferences are criticized by the public, and also tend to create political problems within the scientific body itself. Some of this criticism is probably partly instigated through pique, but is certainly legitimate when it concerns science and society, and also when it concerns inter-university and inter-academic rivalries rather than their cooperation. It seems, however, that there is a strong sentiment among some of the most able and most thoughtful scientists in the United States and the British Commonwealth favoring this method of International Conferences, in spite of its lack of continuity and assured economy. The underlying implication, however, is the desire for conservative leadership, and the complete avoidance of Governmental control. For the reasons stated, it is particularly important that a careful, comparative analysis be made of the objectives and directives and organization of the Russian Academy of Sciences, the Royal Society of London, and the NAS of the United States. Probably no study by scientists of the impact of science on society could be more salutary for science and society. Such a study might serve to bridge certain troublesome difficulties which have arisen between the humanities and the sciences, particularly in the still largely theoretical fields of ideology and the "social sciences."

The answers to the questionnaire, plus additional correspondence, intimate, to date, that the most effective organized method of International cooperation in science is by means of the International Scientific Unions. This is, however, only a majority opinion--and also only a majority opinion of the available (Anglo-American) officers of the Unions.

To quote A. V. HILL, President of the ICSU and Secretary of the Royal Society of London: "The important thing in all this, I think, is to collaborate, for by the actual process of collaboration we learn to understand each other and to find out how it should be done. Solvitur ambulando."

The International Scientific Unions have had more experience, both during war and peace, in all of the above-mentioned problems in science and its social relations than any other type of International scientific organizations. The responsible officers of these Unions are better aware, and consequently better prepared, to deal with these problems, and to improve their methods in dealing with them.

PART V--CONCLUSIONS AND RECOMMENDATIONS

Introduction--"Only in their natural settings can we fully understand the languages, literatures, codes, ideas, interests and moralities of peoples unlike ourselves" (ISAIAH BOWMAN, New York Times, February 21, 1944).

"Molto bello, I agree with every word. Unfortunately, however, Italy has never been in a position where she could anticipate having access on equal terms to raw materials" (MUSSOLINI to SUMNER WELLES, February 25, 1940, quoted from The Time for Decision, Harper and Brothers, Publishers).

"It makes more than ever clear in my own mind the truth of what your President has said, that one of the essentials to a lasting peace is freedom of information" (NEVILLE CHAMBERLAIN to SUMNER WELLES, March, 1940, ibid.).

"Senators and Congressmen (legislators) are generally more responsive to opinions that come from voters in their own districts than to resolutions by a society with which they have no personal contact" (Editorial in News Letter, Mining and Metallurgical Society of America, November 15, 1943).

"There is an unfortunate tendency in easy times for the positions of responsibility to fall into the hands of men who are of the 'committee' or 'organization' type, for there are always available a number of men who like such assignments and perform adequately when not under pressure, but who may not have the energy and leadership to organize and direct a great program. This is particularly true when there is a tendency, quite naturally, to 'honor' a man because of his distinction rather than to select a man because he is the one on whom you would like to rely in a crisis like the present one" (K. T. COMPTON to R. M. FIELD, personal communication).

The "natural settings" within the National boundaries of any sovereign area include the discovery, exploration, and exploitation of all useful materials at, or near, the surface to a depth of one or more miles. The discovery, exploitation, and development of the useful materials depend primarily upon the scientific and technological ability of the inhabitants of the area. The scientific and technological ability of any Nation depends, largely, upon its ability to exchange information with the technical experts of other Nations. The useful materials are frequently referred to as "raw materials", or those materials without any, or all, of which a Nation cannot manufacture the articles which it desires. All National and International trade in manufactured articles depends first of all upon access to "raw materials" and technology. Private enterprise has made great contributions to science and technology, but this is not recognized in the cost-sheets of our National budget.

We have known for hundreds of years that the growth of science and technology has been most rapid in those countries which have had the most complete access to the required raw materials. The industrial progress of any Nation depends, first of all, upon the interdependence of technology and raw materials. With relatively recent acceleration in the growth of science and technology, industrial progress has required a greater quantity and variety of raw materials. Compare the amount and variety of raw materials needed by Great Britain when it had already created its Empire, with the amount and variety of raw materials which Great Britain now needs to even maintain a "Commonwealth of Nations." Compare Great Britain and Italy, from the same point of view, immediately after the signing of the Treaty of Versailles. This is an example of the relation of geoscience to geoeconomics and geopolitics. We continue to learn, through the acceleration in the growth of science and technology, that all Nations are not equally favored in the quantity, quality, and variety of their raw materials; and that some Nations have an excess of what they need while others are either deficient or entirely lacking in certain of their requirements. Science, through synthesis (physical and organic chemistry and engineering, etc.),is learning how to help to alleviate some of the difficulties of this geoeconomic problem, but it cannot hope to solve the

problem without also careful consideration of the excess raw materials within certain National areas. This knowledge is acquired through science and technology, and especially through the earth-sciences, such as geology, geophysics, geochemistry, and biology.

The natural setting of any Nation also includes the character and diversity of its topography and climate with the consequent biology and ecology. It is this physical superficial variety in geography which must be still more fully understood in order to appreciate the origin of the more obvious differences in the "codes, ideas, interests, and moralities of people unlike ourselves." The basis of this knowledge also rests on science.

The future rôle of science will be increasingly social in that science and human affairs have become inseparable. Popular science may no longer be defined only in terms of the marvels of inventions and new gadgets; popular science must also include the relation of science to society and the sincere attempt by scientists to see that this information is available not only to a few favored individuals or groups, but to all elements of society through whose cooperative efforts their developed environments have been created.

The proper relation of science to Government has been seriously neglected by our scientific leaders and their organizations. Although readily available, there is little or no "freedom of information" even in the democracies between our legislative and scientific organizations. This impractical situation is illustrated by many instances of well-meaning, but unnecessarily confusing and debatable, legislative acts and proposals in the United States, such as Senate Bill S-702 and its relation to the directives and responsibilities of the NRC of the United States and its parent organization, the NAS. Surely we need better liaison between science, public opinion, and Government than now exists through the separate deliberations of National scientific societies or academies and of "Senators and Congressmen (who) are generally more responsive to opinions that come from voters in their own districts." It is in the fields of medicine and engineering that scientists and technologists appear to have gained the most experience in improving the liaison between science and society through economic necessity. It is suggested that this same necessity also exists in the whole complex area of science and International affairs, and that scientists have not yet thoroughly and scientifically considered this necessity as an ever-increasing responsibility in the complete rôle of their activities. During the past two years we have had an excellent demonstration of the necessity of science in the art of geowar, and the remarkable recognition by scientists of this necessity. Will scientists equally recognize the necessity of their even greater responsibilities in helping to prepare for the period of reconstruction? The time is now and it is still possible in the democracies for scientific men to select, for this purpose, those leaders whom they particularly trust in "an emergency."

Conclusions--According to this Memorandum the International Scientific Organizations which seem to have operated most continuously and effectively from 1919 to 1944 are the International Unions of Astronomy, Chemistry, Geodesy and Geophysics, and Biology. The International Union of Pure and Applied Physics appears to have been the least active and the least valued by its officers and members, either for the promotion of fundamental or applied physics. Due to the lack of expressed opinion (to date) on this matter by either the British or American officers of the Union, it is necessary to note the information provided by the Director of the recently formed American Institute of Physics, and by the President of the Massachusetts Institute of Technology.

"I have not, myself, been familiar with the activities of the International Union of Pure and Applied Physics . . . . Until the Nazis began to close the laboratories of Germany it was the rule all over the world that physicists traveled freely. They could always enter a physics laboratory anywhere. They would be cordially received and shown all of the researches in progress. The personal acquaintance across boundaries have always been close and numerous. I want to emphasize this because it has practically been very close to an ideal International cooperative arrangement and has been far more effective than any formal organization of Unions or Associations that has ever existed in science" (H. A. BARTON, August 21, 1944).

"In so far as I can evaluate the matter, there has been no International organization of physicists which has been effective or significant. . . . . Whether or not physicists have lost good opportunities through failure to develop a stronger interest in formal International organization is rather hard to evaluate. I have seen much of stimulus and value in a few of the International organizations in other fields such as the International Congress of Applied Mechanics. . . . I am inclined to think that the physicists generally look upon their scientific societies of physics as distinctly 'professional' and they prefer to let their participation in such more inclusive bodies as the Academy and Association of the American Institute of Physics be an expression of their active interest in such border questions as 'The importance of physics on society' and so forth. . .

Finally I would say that I think an International Union on Physics could be successful if an enthusiastic group of young physicists in different countries were to approach the problem with necessary zeal. Otherwise, I do not think such a Union would be successful or worth much time and effort" (K. T. COMPTON, August 21, 1944).

With the possible exception of the chemists, the primary scientists suggest that they can accomplish more in the promotion of their technical interests without the organization of an International Union. It is further implied that they prefer to consider the impact of their technology on society within their National societies and National Academies. It would seem, therefore, that these National societies, National institutes, and National Academies have a special responsibility in the problems of science and its social relations, particularly in relation to mathematics and physics.

One of the most active International Scientific Unions--with also particularly active National Committees--is that of Geodesy and Geophysics. It is in this field of the application of physics to the study of the composition and structure of the Earth that physicists seem to be more familiar with, and more interested in, the border-lines of science and human relations. The geophysicists also seem to be impelled by the same urge for continuous organized International cooperation as the astronomers, because of their mutual need of continuous, world-wide, field-observation as well as the interchange of the latest laboratory techniques and apparatus.

Geographers and geologists seem to be less definitive in their statements on International Organizations. Further data are needed, but the American geographers, at present, do not seem to feel the need of either the present International Union or even an International Congress. The geologists have no Union but have held successful Congresses--the last in Russia. At present some of the leading American geologists are concerned with the organization of an American Geological Council, patterned particularly on the American Institute of Physics and supported by National, founder, geological, and geophysical organizations.

In the United States it appears that the physicists, geologists, and geographers (both fundamental and applied) are favoring separate, technical National Organizations in the approach to International problems. The recent statement (Scientific Monthly, August, 1944, p. 95) by ISAIAH BOWMAN, President of Johns Hopkins University and one of America's most eminent geographers, is pertinent to the International aspects of the close relation of history, science, and the humanities in research and in education. "We should make a Ph.D. mean something more than proficiency in a small sector of a great subject. A man should be capable of thinking about the meaning and the applications of his science, and not merely about a job in teaching 'courses' or advancement in salary in an industry by knowing enough to hold his job."

It would seem that the fields of anthropology and archeology have not been sufficiently explored from the International point of view, especially by the ICSU and its Committee on Science and Its Social Relations. Any Nation may be proud of its archeology without interfering with the same pride in any other Nation. Anthropology may be a somewhat delicate matter from the purely racial and National point of view; however, the natural self-interest of a group of people in themselves is best promoted by their personal participation in the required cooperative research. . . . "in our recent study of the Navajo Indian Problem I doubted if anywhere else in the world we could find a parallel to the extent of scientific research conducted as a basis for the reconstruction and human betterment program" (C. T. LORAM to R. G. HARRISON, 1940). The success of this method is especially well illustrated by H. S. COLTON and his staff, of the Museum of Arizona at Flagstaff.

In western Europe in the Mediterranean Area, in the Far East, and in Mexico, archeologists have already demonstrated both the right and wrong methods in International scientific cooperative research. The same is true in South America. Because of recent developments of essential techniques, from such diverse subjects as aerial photography to stratigraphy, the opportunities for inter-scientific and International cooperative research, from the geoscientific point of view, offer great possibilities.

Of all the natural sciences, probably biology--particularly botany--has the most promising future opportunity for promoting the welfare and comity of Nations. "The natural sciences are a particularly fruitful field for International collaboration because they are themselves International; basic physical and biological laws are the same everywhere and are universally accepted. There is already a good deal of collaboration but much more could be done. Joint planning and exchange of information, services, materials, and personnel could and should be carried out in such a way that Nations would be encouraged and assisted in enlarging agricultural research, applicable to

their problems, while costly duplication could be reduced. . ." (From Final Act and Section Reports, United Nations Conference on Food and Agriculture, Hot Springs, Virginia, May 18 - June 3, 1943, p. 54).

Of particular significance is the growing appreciation by horticulturists of the intimate relation of plants to both the physical and cultural needs of all Nations and races. Closely related to victory gardens, garden clubs, and landscape architecture, is the increasing popular interest and appreciation of the preservation of wild life in such sanctuaries as National reservations and National parks. Probably in no border-line of natural science is the amateur taking a greater and healthier interest in the relation of technology, economics, and politics to human affairs than in horticulture.

The problem of languages and International inter-communication has been as much, or more, discussed by scientists than by humanitarians. Only the mathematicians and the chemists have developed a fully accepted symbolism or "shorthand" which is truly International. The biologists and paleontologists of all countries continue to use Latin and Greek as basis for their classifications of animals and plants. These forms of International language, however, are effective only among scientists themselves and hinder rather than promote popular science both Nationally and Internationally. No characteristic of a race, or of a Nation, is so thoroughly a human characteristic as language. Too great insistence at International meetings by the French that theirs be the "court language" has aroused serious International jealousies. Also because of their wide colonization and consequent technical and economic advantages, the English-speaking scientists have expected "foreign" scientists to speak English. This disadvantage to the art of International intercommunications has been enhanced by the educational policies of both American and British universities--particularly in their graduate schools--with the consequent decrease of the natural collaboration of the sciences and the humanities. The recent experiments in Esperanto and Basic English, or any other International language, illustrate mechanical methods for dealing with a fundamentally non-mechanical problem. The recent experiments by the Army and Navy schools, in teaching our soldiers and sailors the rudiments of such languages as Japanese, Chinese, and Polynesian dialects, should be carefully considered by American schools and colleges.

The resumption of International scientific cooperation in fundamental science, as well as in science and its social relations, depends primarily upon the reservoir of scientific personnel in the about-to-be liberated countries, especially the smaller countries whose scientists have contributed so much to the progress of science and philosophy. American and British organizations--both universities and industrial corporations--have rendered a great service to the salvage of European scientists during the war. How many of these expatriate scientists will be ready and willing to return to their own countries and take active part in their reconstruction? In the United States there is already some evidence that these expatriates are planning not to return to their native lands. Entirely aside from the temporary technical advantage to this country, the concentration of the best European technical brains in North America and Britain will still further impoverish those already ravaged civilizations whose reconstruction depends fully as much on technical as on political leadership.

Finally, there is a serious need for an International scientific periodical devoted to the subject of science and its social relations. The English scientific periodical, Nature, and the official publications of the American Association for the Advancement of Science, Science and The Scientific Monthly, have recently helped to restore the philosophical and humanitarian aspects of science, so seriously neglected by educational institutions during the past 50 or more years.

Recommendations--It has been definitely stated by the Allied Governments that postwar planning must be carried on during the winning of the war. The British, Russian, American, and Chinese Governments are already engaged in attempts at solving political, economic, and educational problems of the postwar period. On the assumption that science and technology are fundamental techniques in International relations, and that fundamental science affords an excellent opportunity for the improvement of methods in the art of International collaboration, the following suggestions are submitted as part of this Memorandum:

(1) The Foreign Secretaries of the Russian Academy of Science, the Royal Society of Great Britain, and the National Academy of Sciences of the United States should explore the possibilities of an inter-Academy study of their International relations in those phases of science which are of benefit to all men and inimical to none.

(2) The International Council of Scientific Unions, through its British and American officers, should simultaneously prepare a memorandum for all Governments which have adhered to the International Scientific Unions, on how the Unions may best collaborate in postwar research and educational problems.

(3) The Division of Foreign Relations of the National Research Council of the United States should continue to advise the National Academy of Sciences of the United States in all International scientific matters which may, or may not, be in the self-interest of scientists of the United States, their institutions, and their related responsibilities to the welfare of their countrymen.

WALTER B. CANNON
Chairman, Division of Foreign Relations of NRC, Foreign Secretary of NAS

RICHARD M. FIELD
American Representative, Committee on Science and Its Social Relations of ICSU, Division of Foreign Relations of NRC

APPENDIX G--REPORT OF SPECIAL COMMITTEE FOR COOPERATION WITH INTERNATIONAL COMMISSION FOR STUDY OF TIDAL WAVES, 1943-44

L. P. Disney, Chairman
P. Byerly H. N. Eaton W. F. McDonald

Information has been collected relative to two seismic disturbances, one of which resulted from the earthquake in Chile on April 6, 1943, and the other from the earthquake in New Britain on January 11, 1941.

Chile--On the basis of instrumental reports, an earthquake occurred in the vicinity of Valparaiso at $12^h\ 07^m$, 60° west meridian time, April 6, 1943, with location of epicenter approximately 32° south latitude, 70° west longitude. A seiche set up by this earthquake was recorded on the marigram of the tide gage at Valparaiso, Chile, which is maintained on a cooperative basis by the Republic of Chile and the United States Coast and Geodetic Survey. The first indication of the shock appeared on the marigram about $12\text{-}1/2^h$, 60th west meridian time. For a period of about six hours the disturbance was quite pronounced, the average amplitude of the seiche being about 2-1/2 feet with an average period of about one-half hour. Following this the amplitude was dampened somewhat but the trace on the marigram indicated that the seiche continued for approximately 18 more hours with an average amplitude of about one foot.

New Britain--A seismic seiche set up in Rabaul Harbor is discussed by N. H. FISHER in his paper, The Gazelle Peninsula, New Britain, Earthquake of January 11, 1941, published in the Bulletin of the Seismological Society of America [January, 1944]. This seiche is recorded as having a maximum amplitude of one foot and a period of ten minutes.

APPENDIX H--REPORT OF SPECIAL COMMITTEE ON GEOPHYSICAL AND GEOLOGICAL STUDY OF OCEANIC BASINS, 1943-44

H. H. Hess, Chairman

W. H. Bucher	L. L. Nettleton	P. A. Smith
R. E. Dickerson	C. S. Piggot	H. T. Stetson
M. Ewing	F. P. Shepard	T. W. Vaughan
D. T. Griggs	D. C. Skeels	

The Committee remains in a state of apparent suspended animation since many of its members are in the armed forces or are involved in work for the armed forces. Much of this work is secret or confidential and cannot be elaborated on during the war.

A great amount of information has been gathered by the Navy which will be of value in the research fields of interest to this Committee after the war. Many new techniques and instruments have also been developed.

Some concern is felt that information will be lost or mislaid in the course of being assigned to vast Government archives at the end of the war. Since the present membership of the Committee is well disposed to keep track of much of the material, it is hoped that such losses will be kept to a minimum, but the assistance in this matter of all Members of the Union interested in oceanic basins is solicited.

Continuation of investigation of gravity at sea, it is believed, is the most important project for consideration immediately after the termination of hostilities. If it could possibly be arranged to make use of present naval bases in the Southwest Pacific Area from New Zealand to New Guinea for a submarine gravity-measuring expedition, it would be highly desirable. To do this all plans and official arrangements would have to be made so that work could start as soon as the fighting stopped, but before the bases were abandoned and submarines withdrawn. This Committee may appeal to the Executive Committee of the Union for assistance in such a project during the coming year.

APPENDIX I--REPORT OF SPECIAL COMMITTEE ON GEOPHYSICAL AND GEOLOGICAL STUDY OF CONTINENTS, 1943-44

W. T. Thom, Jr., Chairman

L. H. Adams	C. L. Garner	J. B. Macelwane
Perry Byerly	Beno Gutenberg	Paul H. Price
M. G. Cheney	N. H. Heck	L. B. Slichter
R. A. Daly	H. H. Hess	H. T. Stetson
E. DeGolyer	F. W. Lee	W. H. Twenhofel
Maurice Ewing	A. I. Levorsen	B. B. Weatherby
J. A. Fleming	C. R. Longwell	G. P. Woollard

Although the pressure of war-emergency work has absorbed the time and energies of most members of the Union's Special Committee on Geophysical and Geological Study of Continents, a few members have been able to continue continental research, and major contributions to "the geophysical and geological study of continents" have recently been made through International cooperative arrangements involving several Governmental agencies and National and International geoscientific societies.

As an example of the results of such cooperation may be cited particularly significant progress which has been made during the past year along geodetic and cartographic lines--since recent International cooperative projects for triangulation, airplane-photography, and air-navigation-chart construction are resulting in the completion of an almost world-wide set of airplane-photographs and uniform-scale base-maps such as are essential prerequisites for effective regional study of continental land-masses. This work, done largely at the instance of the Army Air Corps, has been accomplished with the hearty and effective cooperation of many other organizations and agencies both at home and abroad and has constituted a monumental example of the advantages of broad collaboration for mutual benefit.

A second major mapping project--the construction of a Tectonic (Structural) Map of the United States--has also been completed under the joint auspices of the Division of Geology and Geography of the National Research Council, American Association of Petroleum Geologists, and United States Geological Survey. The Geological Society of America has likewise sponsored three cooperative compilation projects of great scope and significance, namely: The preparation of a new geologic map of North America; the preparation of a geologic map of South America; and the compilation of a glacial map of North America. And the American Association of Petroleum Geologists is similarly sponsoring the cooperative preparation of a comprehensive volume or series of volumes on "The geology of South America."

From what has just been said it will be seen that we are now about to receive the base-maps, airplane-photographs, and areal geologic maps needed as bases for a really adequate cooperative geophysical-geological study of the lithologic composition and structural make-up of the North American Continent. Such a study will involve a regional compilation of major and minor tectonic patterns, both directly visible in the airplane-photographs of the exposed-shield region of central Canada, and indirectly reflected by the areal geologic and geophysical maps which now cover nearly all of the "covered-shield" (interior lowland) region of Canada and the United States. It will also involve a careful study and analysis (and probable extension) of the recent geodetic surveys along the Alcan Highway--since these surveys have linked together older triangulation-systems into a single system reaching from the Atlantic to the Pacific and from the tip of the Aleutians to southern Mexico, and now make possible a direct comparison between regional and local deflections of the vertical over most of North America--with prospective enormous amplification of such comparisons if and as soon as the Alaskan-Aleutian geodetic system can be connected with that of Siberia and interconnections can be completed between the North American and South American triangulation-nets.

Having in mind the developing geodetic-geological-geophysical picture just described, and some of the problems described in the American Association for the Advancement of Science - American Geophysical Union "Symposium on the surface and subsurface exploration of continental borders", the X-type gravimeter loaned to the American Geophysical Union by the Humble Oil and Refining Company has been further used during the past year--first for the establishment of additional gravity profiles in eastern, central, and northern New England, and later (by loan to the Dominion Observatory of Canada) for the completion of an integrated regional system of pendulum-, deflection-, and gravimeter-stations, extending from Nova Scotia, New Brunswick, and the general St. Lawrence Region on the north to the Virginia-Carolina Border on the south--a system which should, as soon as possible, be extended eastward to the outer margin of the (submerged) continental shelf, and southward and southwestward to connect with the areas of intensive gravitational study in the southern United States and Cuba.

Turning from the general studies of continental make-up and structure to somewhat more specific studies of the dynamic causes and mechanical processes responsible for the recurrence of mountain-building movements, it can also be reported that the cumulative and cooperative efforts of many geologists and geophysicists have, at last, fitted together a fairly adequate quantitative working hypothesis as to how, when, and why the deformation and uplift of the Eastern Rocky Mountain range-and-basin region have taken place, and as to how, when, and why this area has been repeatedly disturbed by profound volcanism and by the development of adjacent thrust-fault systems featured by crustal shortenings and differential lateral crustal movements measurable in tens of miles.

Also, in the tectonically younger and more active parts of the American Cordillera (extending from the Pacific Coast of the United States into southern Mexico, Central America, and the Andean region of South America) critically important geophysical-geological information has been and is being, or can be, obtained: (1) From several different types of seismic "observation-and-analysis" study; (2) from recent studies of the sea-floor topography along the coasts of Mexico, Central America, and South America; (3) from the geological and geophysical structural information yielded by the intensive oil-field explorations in California areas; (4) from manifold geophysical-geological studies of areas of recent volcanic eruption as, for example, around Paricutín (Mexico), Flagstaff (Arizona), Lassen Peak (California), and the Katmai-Aleutian Region of Alaska; and (5) by such further geodetic-and-astronomic studies as may reveal the relation between the horizontal and vertical components of thrust-faulting; the causes and general nature of such movements; and the rates at which differential lateral movements are now taking place in the Earth's more active tectonic zones as, for example, in the Andean Region between Valparaiso, Chile, on the west, and Buenos Aires and Cordoba, on the east.

In conclusion, it should be reemphasized that geophysical-geological studies (such as have just been either described or projected) can only be carried out under a broad intra-National and international cooperation and collaboration, and necessarily involve a free and friendly exchange of ideas and information. Studies of this sort will necessarily greatly facilitate and expedite the practical exploration and commercial development of the mineral natural resources of all countries--but will do so without giving preferential position or competitive advantage to any group or to any Nation. Consequently, such geophysical-geological study will contribute to the happiness and economic well-being of all peoples in much the same manner that International medicine has long been contributing to world-health and world-unity.

APPENDIX J--REPORT OF SPECIAL COMMITTEE ON AUDIT FOR CALENDAR YEAR 1943

A. G. McNish, Chairman J. B. Kincer

Your Special Committee on Audit, reporting as of May 31, 1944, has made an examination of the accounts of the American Geophysical Union for the year ending December 31, 1943. It finds that the statement of the General Secretary is correct as given except that through failure to enter two checks, one in the amount of $120.20 for typing master-copy of the Transactions and one in the amount of $119.40 for services to the General Secretary's Office, the disbursements for the year were $7,665.53 instead of $7,425.93, leaving a balance of $10,247.71 instead of $10,487.31 as given. This balance is covered by a bank balance of $10,247.71 when due allowance is made for checks outstanding as of December 31, 1943.

These changes result in an increase in the amount given for the cost of the Transactions by $120.20 and in the cost of services to the General Secretary's Office in the amount of $119.40

with corresponding corrections in the financial statement. These changes have been carried into the new accounts for 1944.

Your Committee has found that the records have been excellently kept, that all receipts and disbursements (see appended statement) are duly substantiated, and that the methods of handling the accounts are clear and efficient.

[Note: The accompanying financial statement for January 1 to December 31, 1943, has been corrected and in form as approved by the Special Committee on Audit.]

Financial statement January 1 to December 31, 1943
(As approved by Special Committee on Audit)

Receipts		
Cash balance, January 1, 1943, per audited accounts for 1942		$ 6,781.35
American Geophysical Union	$4,813.98[a]	
Special Fund	250.00[b]	
Bowie Medal Fund	203.60	
Washington Assembly	1,513.77	
Dues, 1941, 1942, 1943, 1944, 1945		5,994.00
1941	$ 27.00	
1942	171.00	
1943	5,731.00	
1944	64.00	
1945	1.00	
National Research Council in payment of vouchers		397.57
Sales of Publications		2,082.22
Transactions	$1,097.83	
Reprints	917.39	
Bibliographies of Hydrology	15.18	
Special Exhibit Maps	49.25	
International Union of Geodesy and Geophysics	2.57	
Contributions to Special Fund ($14.00 + $2,641.00)		2,655.00
Miscellaneous including overpayments account discounts		3.10
Total receipts ($6,781.35 + $11,131.89)		$17,913.24
Disbursements		
Transactions of 1942		$ 1,548.70[c]
Transactions of 1943		1,239.66[d]
Drafting	$159.60	
Photography	108.77	
Typing master-copy	943.80	
Proof-reading	27.49	
Reprints		1,001.63
Articles from Transactions of 1942	$727.87	
Reprints of complete Part I, Transactions of 1942	273.76	
List of Members, October 15, 1943 (71 pages)		375.43
Typing master-copy	$110.60	
Proof-reading	14.34	
Printing	250.49	
Photostats of Special Exhibit Maps		18.94
Expenses of General Secretary's Office		1,891.65
Services, including income tax	$1,802.61	
Miscellaneous	89.04	
Forwarded		$ 6,076.01

[a] Less $13.00 not properly entered in books in 1942 for Special Fund.

[b] Plus $13.00 erroneously entered under Miscellaneous in books in 1942.

[c] Total cost of Transactions of 1942: [$460.90, Part I + $1,548.70, Part II = $2,009.60] + [Cost of preparing master-copy, $211.50, drafting and photography, + $907.00, typing, + $37.25, proof-reading + $17.76, paper for copy = $1,173.51] or in total $3,183.11 for 741 pages in edition of 2,200.

[d] Total cost of Transactions of 1943 [Printer's bills to be paid in 1944 ($1,275.21, Part I, + $1,726.72, Part II, + $350.82, Part III = $3,352.75)] + [Cost of preparing master-copy paid in 1943 ($268.37, drafting and photography, + $943.80, typing, + $27.49, proof-reading = $1,239.66)] or in total $4,592.41 for 888 pages in edition of 2,600.

Disbursements--Concluded		Forwarded	$ 6,076.01
Committees			240.05
Membership		$203.28	
Finance		36.77	
Sections			8.97
Geodesy		$6.35	
Seismology		2.62	
Meetings			260.72
Twenty-Fourth Annual Meeting at Washington, D. C.		$259.04	
Regional Meeting at Corvallis, Oregon		1.68	
Bowie Medal, engraving			8.00
Postage, express, telegraph, and telephone			733.03
Stationery and supplies			338.75
	Total disbursements		$ 7,665.53
	Balance December 31, 1943		$10,247.71
Riggs National Bank (Chevy Chase Branch)			
American Geophysical Union		$5,633.34	
Special Fund		2,905.00	
Bowie Medal Fund		195.60	
Washington Assembly		1,513.77	$10,247.71

Bills receivable			
Publications			$ 566.19
Transactions		$158.04	
Reprints		406.75	
Miscellaneous		1.40	
Dues			555.00
Postponed account 8 Members in enemy countries		$69.00	
Unpaid account 1 Member for 3 years, 1941-43		9.00	
Unpaid account 43 Members for 2 years, 1942-43		257.00	
Unpaid account 74 Members for 1943		220.00	
National Research Council allotment for fiscal year ending June 30, 1944			400.00
Sales of Transactions and reprints and other publications (estimated)			2,000.00
	Total bills receivable		$3,521.19
Bills payable, (a) American Geophysical Union			
Transactions of 1943 (2,600 copies)			$3,352.75
Part I (332 pages), printing		$1,275.21	
Part II (estimated 454 pages), printing		1,726.72	
Part III (102 pages), printing		350.82	
Reprints, Transactions of 1943 (estimated)			1,000.00
Packing and mailing of Transactions of 1943 (estimated)			200.00
	Total bills payable (a)		$4,552.75
Bills payable, (b) Washington Assembly (estimated)			$1,513.77
Reprints (deducting free copies), Seismology		$ 90.00	
Scientific Hydrology (allotted by Executive Committee)		1,000.00	
Volcanology (allotted by Executive Committee)		300.00	
Postage and services in mailing		123.77	
	Total bills payable (b)		$1,513.77

Recapitulation

	A.G.U.	Bowie Medal Fund	Washington Assembly	Special Fund
Cash balances	$5,633.34	$195.60	$1,513.77	$2,905.00
Bills receivable	3,521.19	0.00	0.00	0.00
Total assets	$9,154.53	$195.60	$1,513.77	$2,905.00
Bills payable	4,552.75	0.00	1,513.77	0.00
Net assets	$4,601.78	$195.60	0.00	$2,905.00

Equipment owned by American Geophysical Union

One 18-inch large primer Burroughs typewriter, serial No. 60A232450	$190.80
One 10-inch elite Royal typewriter, serial No. KHM-2076351	100.31
Two 4-drawer, 5x8-inch steel filing cases (gift)	0.00
Two steel posture chairs	22.00
One Globe-Wernicke, 2-pedestal, flat-top steel desk, 60x34 inches	49.18
One Triner postal scale, 4 lbs. by 1/2 oz.	16.20
One Arrow stapler	6.75
	$385.24

APPENDIX K--REPORT OF SPECIAL COMMITTEE ON TIME-SIGNAL SERVICE, 1943-44

H. E. McComb, Chairman

Perry Byerly	W. A. Lynch	P. Sollenberger	C. H. Swick
Daniel Linehan	J. B. Macelwane	H. T. Stetson	H. O. Wood

It is gratifying to report that the United States Naval Observatory time-signal schedules, as broadcast by the United States Naval Communications Service, and the Standard-Frequency broadcasts from the National Bureau of Standards have met the most urgent needs of field-parties and others engaged in astronomical, geodetic, magnetic, and seismological work during the year. As in former years, special time-signals have been furnished by the Navy for field-parties operating in remote areas.

The Committee recommends that agencies responsible for the maintenance of these time-services be commended by appropriate resolution for maintaining these schedules without serious interruption.

APPENDIX L--REPORT OF SPECIAL COMMITTEE ON COSMIC-TERRESTRIAL RELATIONSHIPS, 1943-44

H. T. Stetson, Chairman

C. F. Brooks	J. A. Fleming	E. O. Hulburt	W. T. Thom, Jr.
H. H. Clayton	N. H. Heck	H. Landsberg	N. Wiener
J. H. Dellinger	J. F. Hellweg	J. Q. Stewart	

As has been stated in the last two annual reports, much of the time of the personnel of our Special Committee on Cosmic-Terrestrial Relationships has been consumed in scientific investigations contributing to the war-effort. It is possible, however, to state that considerable progress has been made in the work of this Committee during the year ending June 30, 1944. It is to be emphasized that systematic records of cosmic data have been maintained and, in some instances, actually increased, both in quantity and in quality. This in itself is important, since any interruption of continuous records of cosmic phenomena seriously interferes with subsequent study of the interrelationships of geophysical data.

The early months of 1944 have seen the lowest record of sunspot-numbers for over a decade, indicating that we are now passing the so-called minimum of solar activity. However, the new solar cycle is now under way, for before the period of actual minimum sunspot-activity has occurred the first spots of the new coming activity invariably appear.

The first group of sunspots definitely defined as belonging to the forthcoming cycle was observed on May 16, 1943, and its magnetic polarity determined as definitely opposite from that of the old sunspot-groups by the Mt. Wilson observers.

The new sunspot-group appeared on the Southern Hemisphere of the Sun at a mean latitude exceeding 40° from the solar equator. While there is some uncertainty involved in predicting the exact time of the next sunspot-maximum, one may confidently forecast increasing numbers of these solar disturbances in the next four or five years to be followed by gradual decline thereafter.

The generally adopted duration of a sunspot-cycle is 11.3 years, but the actual interval between maxima or between minima may vary from nine to 17 years. The interval between maxima

of the last few cycles has been definitely less than the average 11.3-year interval. The last maximum occurring in the middle of the year 1937 followed the previous maximum of 1928 by only nine years.

In this connection it should be emphasized that the ability to forecast wave-lengths and frequencies for best radio communication between various parts of the world rests in no small measure upon the ability to anticipate the occurrences of these disturbances on the Sun that have been known for 300 years.

Representatives of your Committee have met on various occasions for participation in conferences at the Blue Hill Meteorological Observatory, at the Massachusetts Institute of Technology, at the Department of Terrestrial Magnetism of the Carnegie Institution of Washington, at the National Bureau of Standards in Washington, and at the Cosmic-Terrestrial Research Laboratory in Needham.

Because of the importance of the relation of solar activity to radio communications, Dr. JOHN Q. STEWART has continued his work on the solar cycle, although much of his time has had to be devoted to war-training courses and the preparation of a comprehensive text on navigation.

Dr. C. F. BROOKS of the Blue Hill Meteorological Observatory reports that continuous records of total direct and indirect solar radiation on a horizontal surface and of the solar beam at normal incidence have been continued through the eleventh year of record (since the fall of 1932). On clear days when there is little variability of intensity, two pairs of screenings have been made with SCHOTT filters OG_1 and RG_2. The work here has continued in close cooperation with the Solar Radiation Supervising Station of the United States Weather Bureau, Irving F. Hand in charge. He has recently installed recording apparatus for total solar and sky radiation on a horizontal surface and for illumination-intensity on a horizontal surface on top of the Federal Building in Boston.

H. H. CLAYTON is now actively engaged in cooperating with the Weather Bureau on research of the relation of solar changes to changes of weather, results of which will be published later.

Captain N. H. HECK of the United States Coast and Geodetic Survey reports that, with the cooperation of the Department of Terrestrial Magnetism of the Carnegie Institution of Washington, there has continued the cosmic-ray recording at the Cheltenham Magnetic Observatory and the recording of atmospheric electricity at the Tucson Magnetic Observatory. The records from both were sent to the Department of Terrestrial Magnetism of the Carnegie Institution of Washington for processing. The K-numbers for the five observatories of the Survey were furnished the Department of Terrestrial Magnetism. Additional observations of the magnetic diurnal variation and all magnetic elements were made in South America in cooperation with the countries concerned. Magnetic observations were made at repeat-stations in the United States preparatory to publishing the magnetic tables and charts for 1945. The larger magnetic anomalies of the United States were plotted.

Two laboratories that have devoted considerable time to the study of cosmic-terrestrial relationships, in addition to Government agencies, have been that of the Department of Terrestrial Magnetism of the Carnegie Institution of Washington and the Cosmic-Terrestrial Research Laboratory in Needham, Massachusetts, associated with the Massachusetts Institute of Technology. While much of the time of these and other institutions have been devoted to the war-effort, observations have accumulated of general significance, the summary of which can be briefly stated.

Dr. J. A. FLEMING, reviewing the year's progress of the Department of Terrestrial Magnetism, states that "during the year cosmic data were assembled and analyzed (1) to increase the understanding of solar, geomagnetic, and ionospheric relationships and (2) to improve the technique of short-term forecasting of ionospheric disturbances. Electron-density in the ionospheric regions has continued to diminish as the minimum of the 11-year cycle of activity approaches. Some magnetic and ionospheric disturbances occurred, and the isolation of solar regions responsible for terrestrial disturbances was simplified by the reduced solar activity. Solar corona of high intensity and observed activity in flocculi on the disk were found apparently the most promising criteria for anticipation of magnetic disturbances. The beginning of the new sunspot-cycle indicates an early increase of solar, magnetic, and ionospheric activity. Ionospheric absorption, sporadic E-region ionization, aurora, and magnetic bays and character-figures were found to be related in fairly definite ways, in most cases approximating direct proportionality. Methods of obtaining accurate visual records of magnetic phenomena were developed, and one visually recording instrument was constructed. Useful operational material regarding ionospheric disturbances affecting radio circuits was supplied to the Army and Navy.

"Geomagnetic and geoelectric observations continued to contribute further to the field of cosmic-terrestrial relationships. Improvements in both methods and instruments have been made in the Department for measuring ionization of the lower atmosphere. Ionospheric investigations were continued at the Department and analyses made of data gathered at Watheroo (Western Australia), Huancayo (Peru), and College (Alaska). Recommendations for additional ionospheric stations have been made and arrangements undertaken for their operation in the near future.

"In the field of atmospheric electricity there have been further developments of instruments, methods and techniques. Measurements of the potential-gradient at Watheroo have shown that the maximum of the diurnal variation during the Southern Hemisphere winter occurred at about 07^{h} GMT (= GCT) whereas over the oceans the measurements have been found to occur at 17^{h} GMT, although for 17 specifically selected days a close comparison could be found between the diurnal curve for Watheroo and over the oceans. It is believed that the difference could be accounted for on the basis of ionization at the Earth's surface being due to an accumulation of radioactive matter near the ground. On days of high wind the turbulence of the lower atmosphere causes better mixing of the ions, and it is on these days that the diurnal variation of potential-gradient most closely simulates that over the oceans. Similar investigations have been made of the potential-gradient in summer."

At the Needham Laboratory the program of field-intensity determinations has not only been continued but expanded because of the importance of the results in effecting a satisfactory formula for the general problems of radio-communication predictions. Reception from stations in three different bands of the radio spectrum are now being covered through suitable continuous recording apparatus. Copies of these records have been supplied to the Government at Washington. The continued recording of the relative fields of two adjacent beams of the Boston Air Beacon have proved of value, particularly in connection with changes that have taken place during the present emergency. Hourly records of the potential-gradient have accumulated and form a basis for further study of local conditions for conductivity at the ground-level.

There has been an increased number of records showing atmospheric-electric discharges between the Earth and the sky as determined by the point-discharge recorder. Some of these records have been of particular interest to industrial concerns devoted to war-production, and have been supplied gratis.

The investigation of a possible effect of the Moon upon ionization-phenomena at upper levels based on over 18,000 hours of observation has for the time being been completed and published in the March, 1944, number of the Journal of Terrestrial Magnetism and Atmospheric Electricity.

It would appear that sufficient evidence from field-strength determinations exists to show a correlation between the night-time ionization at the E-level and the elongation of the Moon from the Sun. Results indicate a possibility of other causes than tidal phenomena of a gravitational character. Such hypotheses as have been advanced to account for the observed phenomena are given in detail in the paper to which reference is made and need not be repeated here.

At the request of the Editor of the Scientific Monthly, a general article on Cosmic-terrestrial research was published in March, 1944, and has aroused considerable interest from various workers in allied fields of research.

The multiple cosmic-ray counter to which reference was made in last year's report has been in operation during the year in cooperation with the project of the University of Chicago and, while still operating on somewhat of an experimental basis, has yielded many hours of records of cosmic-ray intensities in three parts of the cosmic-ray spectrum.

Through the continued cooperation of SELBY HAAR, the Naval Observatory time-signals have continued to be monitored and the data forwarded monthly to the Needham Laboratory. The results show the continued poor reception on the higher frequencies over the Washington-New York path during the minimum of solar activity.

By invitation of the Section of Geology of the New York Academy of Sciences, a session was held on April 3, 1944, devoted to the subject of variations in geographical coordinates, at which was summarized the existing evidences, the difficulties encountered, and the desirability for international cooperation for redetermining, with all the precision now available, latitudes and longitudes of certain points on the Earth's surface between which tectonic action would appear most likely to cause differential lateral shifts. The interest in the problem stimulated a prolonged discussion during which the desirability was brought out of the redetermination of the longitude of Valparaiso and Buenos Aires--two stations that had been used as intermediary points by GOULD in the de-

termination of the longitude of Cordoba in 1871. It will be recalled that the more recent determination of the longitude of Cordoba showed a discrepancy of one whole second of time from that of the earlier determination. The possibility of the discrepancy being caused by local changes at Cordoba could probably be settled by reobservations of the coordinates of the other two South American cities involved. The paper has been sent to the New York Academy at their request for publication in the Transactions of the Academy.

Because of the inherent global nature of cosmic research, your Committee has endeavored to keep in touch with such representatives of the International Union of Geodesy and Geophysics as were available, with a view to enlarging the effectiveness of the Committee's work in preparation for a closer postwar cooperation with other countries. Because of the responsibility assumed by the Commission on Continental and Oceanic Structure of the International Union of Geodesy and Geophysics for maintaining so far as possible interchange of information with friendly countries, your Committee was asked to prepare a summary of strategic problems in cosmic-terrestrial relationships for the use of the Commission in preparing a comprehensive report that would aid in fostering present and postwar science internationally. Accordingly, a report was prepared covering some of the larger problems in which your Committee has been interested since its inception and, after conferring with members of the Committee most concerned, a copy was transmitted to the Chairman of the Commission on Continental and Oceanic Structure of the International Union of Geodesy and Geophysics and a duplicate filed with the General Secretary of the Union. The report contains certain recommendations that could be directly helpful to the war-effort and, therefore, at this time, cannot be published in full. Such of the material as is not intimately associated with the war-effort is appended to this annual report.

In conclusion, it is believed that special opportunities and special responsibilities confront the Special Committees of the Union, and your Special Committee on Cosmic-Terrestrial Relationships should continue to endeavor to work closely with the other Special Committees toward the realization of the furtherance of geoscience in the postwar world. Your Committee, therefore, is grateful for the cooperation of the several Sections of the Union, and particularly would emphasize such problems of interrelationship as can best be solved through International cooperation. Specific recommendations are made in the report to the International Commission above referred to, an abstract of which follows.

Report on cosmic-terrestrial relationships to International Commission on Continental and Oceanic Structure

Because of the broad specific instructions set forth at the Edinburgh Assembly when the Commission was formed in 1936, the Commission is in a unique position relative to certain fields when cosmic-terrestrial relationships are concerned. These may involve problems both of the Earth's crust and of its atmosphere.

The rather remarkable results that have already been obtained with sensitive gravimeters of the latest type have made evident rhythmic variations in gravity directly attributable to the tidal forces of the Sun and Moon. Comparisons of observations with theoretical calculations of earth-tides should make possible the evaluation of any variations in elasticity and rigidity of the crust at specific locations. It is believed that the Commission should be in a position to see that suitable instruments for this purpose are placed at selected stations in regions of known instability, as well as geologically stable territory. Here one cannot overstress the importance of continuous runs of gravimeters for a sufficient length of time at any one place to include the major rhythms due to predictable causes. The investigation of variations of coordinates not only horizontally but in a vertical direction would undoubtedly be greatly aided by such an investigation.

Variation in coordinates--The problem of variations in geographical coordinates is in itself one of immediate concern to the whole question of continental and oceanic structure. The fact that no triangulation-survey of the Earth's crust can yield data on other than relative movements makes imperative the reconsideration of all available geodetic evidence that points to anomalies in positions determined at well-established points. The astronomical evidences for changes in latitude and longitude are still conflicting. There is undoubtedly room for improvement in method and technique of determinations of latitude and longitude, possibly even involving the adopted positions of the fundamental stars customarily selected.

The Commission, therefore, needs the cooperation of the Commissions on Latitude and Longitude, not only of the International Union of Geodesy and Geophysics but of the International Astronomical Union, as soon as conditions for active cooperation with these Commissions again becomes possible.

It is pertinent to remember here that the International latitude-stations were originally selected along the 39th parallel at suitable intervals for best determining the motion of the pole. Unfortunately the selection resulted in establishing sites for the most part in regions known to be geologically unstable. It is unfortunate that, in the reduction of the observations for latitude, the declinations of the reference-stars were so adopted as to distribute the errors of observation in evaluating the polar motion. This precluded the discernment of the secular drift of any one station with respect to the fundamental geographic coordinates. In the postwar period, it should be possible to rediscuss the whole question of the location of latitude-stations, and the method of adopting star-positions used as fundamental data in the solution of the latitude-problem. Anomalies should not be hastily dismissed as necessarily instrumental errors since the history of science emphasizes the recognition of anomalies as often pointing the way to further discovery. The question of additional latitude-stations should be raised at the earliest opportunity. Such a question is intimately associated with the problems with which the International Commission is concerned, problems which obviously can be solved only through International cooperation on a global scale.

Any question of an east-and-west component of crustal displacement in recent times involves the determination of longitude to the highest degree of precision. Fortunately through the universal use of radio time-signals, longitude may be determined with a convenience and with a degree of precision not possible a generation ago. However, the transmission of time by radio involves the question of the propagation of electromagnetic waves through an ionized medium--the Earth's atmosphere. Evidence already brought forth demonstrates that the velocity of propagation of radio time-signals cannot tacitly be assumed to be the equivalent of the velocity of light as has often been done. An analysis of recent comparisons of longitude has shown that the effective velocity of transmission may vary as much as 30 per cent, dependent upon the latitude and longitude of the path of transmission over which the time-signals are exchanged. The directions as to the duties of the Commission laid down at the Edinburgh Assembly were therefore the more wisely chosen in that in the list of extensive studies outlined to be undertaken, directive (3) specifically states: "Nature and causes of regional and temporary variations in radio transmission and reception."

Time-problem in longitude-determination--The problem of measuring differences in longitude with sufficient precision to detect horizontal displacements involves two operations: (1) The determination of the exact time of transits of stars across the meridians of Greenwich and Washington, respectively, with the highest attainable accuracy; (2) the communication of these times by radio to each of the stations occupied.

As has already been pointed out by LOOMIS and STETSON in the two papers on the subject, which have already appeared, evaluation of small changes in longitude rests upon the fundamental assumption that radio waves conveying the time-signals pass with the same velocity whether traveling with or against the rotation of the Earth--an assumption which, at least for low-frequency waves such as were used in their analysis of the Rugby-Annapolis signals, would appear to be justified.

That evidence has been found that the effective velocity of radio transmission is not the same as that of light, and that the velocity may vary with geomagnetic latitude and with the season, is a fact which, of itself, does not immediately enter into the question now under discussion. Whatever the velocity and path taken by the waves of propagation between Washington and Rugby, we need only suppose that the path and the velocity are the same from west to east as from east to west in attacking the problem of variations in longitude.

Since, however, no determination of longitude can be more precise than the trustworthiness of the constancy of radio-wave propagation in both directions at the moment of comparing time-signals, it is highly desirable that such a fundamental supposition should be tested by experimental methods before adopting without question any results dependent upon time-signal comparisons. A project has therefore been submitted to and approved by the Planning and Projects Committee of the American Geophysical Union which we believe will afford at least a preliminary test of the validity of this fundamental assumption.

The precision obtained by EWING in making gravity-determinations at sea, where the timing-mechanism of the pendulum-apparatus was a crystal-chronometer constructed by the Bell Telephone Laboratories and loaned to the American Geophysical Union, led us to believe that this timepiece could be profitably employed in testing the fundamental assumption relative to the propagation of time-signals by radio. This project proposes, therefore, to transport by airplane a crystal-chronometer capable of maintaining a rate within $0^{s}.001$ per day from Langley Field near the Naval Observatory in Washington to a point in the interior of the country some 2,000 miles west of Washington, the plane to fly at a speed of approximately 200 miles per hour and to

record aboard the plane the Washington signals as received by the crystal-chronometer. Similarly, signals from the moving chronometer would be recorded at the Naval Observatory. Since these time-signals will be received hourly, there should be an apparent cumulative lag in the reception-time of about $0^s.001$ for each successive hour of flight. Assuming that a continuous flight of seven hours can be made before the termination of the journey, there will be an accumulated lag of $0^s.007$ by the time the signals are received over the 1,400-mile base-line--a time considerably in excess of any expected error of which the crystal-chronometer is capable.

In a return journey immediately following, the $0^s.007$-lag should be reduced by approximately $0^s.001$ per hour until arrival of the plane again at Langley Field near Washington. The crystal-chronometer originally synchronized with the crystal-clock at the Naval Observatory should again appear to be in complete synchronization at the end of the experiment. If the experiment performed as just outlined yields the consistent results anticipated, we should have, we believe, sufficiently verified the fundamental assumption as to the constancy of east-to-west and west-to-east transmission of wireless waves, thus removing all shadow of a doubt as to the trustworthiness of data dependent upon time-signal communication. Should there appear a difference in the lag of the reception of the signals in the return journey from corresponding signals received on the outgoing trip, we should probably have made an even more significant contribution to science than the expected results would have presupposed.

With the present precision of star-observations by modern photographic methods, and the precision in timekeeping now attainable through the invention of the crystal-clock and the crystal-chronometer, we have available astronomical tools of much significance to geodesy and geophysics. It would appear abundantly worth while to provide and analyze determinations of longitude with a view to the geophysical significance of such data in the attack on problems concerned with the geologic structure of continents and oceanic basins.

Radio communication--The whole question of radio-wave propagation on a world-wide scale is so complex that the utmost cooperation is desired by geophysicists and radio physicists in the solution of the problem of the ionization of the medium involved, namely, the upper atmosphere.

The Union Radio Scientifique Internationale and Association of Terrestrial Magnetism and Electricity of the International Union of Geodesy and Geophysics have already contributed much to information relative to the ionosphere. Already we have ionospheric stations regularly determining critical frequencies by the reflection-method at widely separated points about the Globe. The extent of the ocean of the upper atmosphere, however, is so great as to make urgent the establishment of many additional such stations at the earliest opportunity. A supplementary field of investigation that has not been undertaken to any great extent by either of the two organizations mentioned is the systematic determination of radio field-intensities at strategically selected points where equipment and personnel could be assigned for continuous recordings.

While critical frequencies furnish the indices for determining the ionic concentration at communication-levels of the atmosphere and thereby make possible certain generalized predictions of usable frequencies, the divergence of such predictions and observed field-strengths at given points is so great as often to make theoretically assigned values for communication-conditions not only inadequate but often quite unreliable.

It is believed that the measurement of field-intensities, furnishing as it does actual conditions of reception at a given time and place and at a given frequency, must ultimately furnish the observational data necessary for predicting conditions of communication from more theoretical considerations. As an analogy one might say that the field-intensity recorder is to the problem of electronic tides in the ocean of the atmosphere as is the tide-gage to the problem of tides in oceanic waters. However well the astronomical and gravitational potentials of the disturbing bodies are known, no mariner would for a moment trust the tide-tables for a given port constructed on any such theoretical basis. Only when tidal theory has been compared with the observed rhythmic surge of the ocean waters at the port in question can the establishment of the port and other factors be evaluated necessary for the computation of tide-tables from the known positions of the Moon and the Sun. . . .

Atmospheric-electric observations--It should be pointed out here that in 1933 there existed some 55 stations in the Eastern Hemisphere established for magnetic observations, some of which also make atmospheric and electric recordings, and in the Western Hemisphere but 17 similar stations. In the next decade, a few additional stations have been established from a recommended list. While probably most of these stations are occupied principally for securing needed magnetic data, it is believed that such stations already occupied for important work could at relatively slight expense add instruments for atmospheric-electric observations such as a few of these are now doing.

In addition to ionospheric or radio observations such as have already been stressed, it is highly desirable that measurements should be made of the potential-gradient of the atmosphere at low levels, and possibly other electrical characteristics such as conductivity, the distribution of large and small ions, and a continuous record of the interchange of electricity between the Earth and the lower atmosphere. These are specific problems which need International cooperation. From observations obtained on the extensive voyages of the non-magnetic ship Carnegie, it appears that the atmospheric potential-gradient attains a maximum over the entire Globe at about 16^h to 18^h universal time (Greenwich mean time). Any adequate explanation of this has not yet been forthcoming. Furthermore, it is known that the fair-weather current flowing between the Earth and the atmosphere is approximately 1,000 amperes for the whole Earth. Any explanation of this or any adequate knowledge of variations in the geographical distribution are lacking until more continuous observations from more cooperating stations distributed over the Earth have been obtained. The solution of the problems of the Earth's electric field, as that of the Earth's magnetic field, must rest upon International cooperation.

Cosmic rays--Another problem of paramount concern is that of the measurement of the variations and the distribution of the penetrating radiation due to cosmic rays. Sufficient data gathered on various expeditions by MILLIKAN, COMPTON, and others have revealed the desirability of continuous recordings of these variations at widely distributed observatories. It is probable that such data not only lead to a better understanding of the nature of cosmic-ray phenomena but must indirectly contribute greatly to the solution of the problems of the upper atmosphere, an absorbing medium capable of changing the cosmic-ray counts. In other words, cosmic rays may yield the kind of meteorological data that could be anticipated from systematically sending aloft to the stratosphere sounding balloons every hour on the hour. It may be stated that a group of stations of this sort utilizing automatically recording Geiger counters has been planned and is now within the process of establishment within the United States.

Ultra-violet radiation--Because of the importance of the impact of solar radiation on the top of the atmosphere in bringing about ionization at high levels and the production and dissociation of ozone at the 25- to 40-km level, it is surprising that there has not yet been established any world-wide program for continuous observations of the ultra-violet light from the Sun and the sky. Such measurements have been made by various methods from time to time over a series of years in specific localities, but nothing like adequate coverage has yet been undertaken, nor have any such measurements persisted for a long enough time to make possible the significant results it is believed would be obtained with the establishment of a coordinated plan for this purpose.

In spite of differences of opinion as to the most desirable methods of making such measurements and the region of the spectrum to be adopted for evaluating relative absorption-bands, it is believed that the most desirable method that could be adopted for carrying out such a project at relatively small cost would be the photographic recording of the solar spectrum obtained with a simple quartz-prism spectrograph. Such photographic records could be photometrically standardized at the time of each exposure. The records from International stations could be allowed to accumulate and, by such agreements as may be obtained later, specific regions of the spectrum so recorded could be utilized for measurement in determining not only the amount of ultra-violet light received at the Earth's surface daily but the amount of ozone present from the intensity of the absorption-bands selected for study. This appears to be one of the most fundamental and urgent problems of geophysics to be undertaken through International cooperation. The results could be expected to yield information as to the distribution of ozone over continents and over oceans--information that relates specifically to the problems of meteorology and to those of atmospheric ionization.

Since the last meeting of this Commission at the International Assembly in Washington in 1939, there has been established at Needham, Massachusetts, a Laboratory for Cosmic-Terrestrial Research operated in connection with the Massachusetts Institute of Technology. At this Laboratory a selected number of the problems, which have been outlined in this report, have been undertaken. Field-strength measurements at broadcast and higher frequencies are continuously recorded and have already yielded significant results. By a comparison of observations of available critical frequencies with field-strengths measured at this Laboratory, it has been possible over a limited period to approximate changes in field-strengths with corresponding changes in ionic concentration at reflection-levels. From the meager data already analyzed, it may be supposed that a change in measured field-strengths of 40 per cent may result from a change in ionic concentration at the E-layer of but a very few per cent. This emphasizes that field-strength measurements may afford a means of examining the fine structure of atmospheric ionization as compared with the more general structure of the ionosphere determined by critical-frequency methods. As an analogy, one might suggest that the method of field-strength determinations bears

somewhat the relation to critical-frequency measurements as does the method of interferometry to that of spectroscopy in the study of radiation.

An analysis of ten-years' records with respect to auroral occurrences leads to the conclusions: (1) That a period of from 24 to 36 hours elapses between the time of solar activity near the meridian and the day of auroral occurrences; (2) that F-layer-disturbances follow quickly the disturbances causing auroral display; and (3) that another day elapses before ionization-conditions at the E-layer are sufficiently disturbed to have blotted out communication at broadcast frequencies.

The close correspondence of solar activity with upper atmospheric ionization as determined from critical frequencies has been remarkably exhibited throughout the last solar cycle. This leaves little to be desired to emphasize the need for continued study of the dependence of upper atmospheric reactions upon solar activity throughout the sunspot-cycle. From measurements made in this country and abroad, it would appear that the change in the state of atmospheric ionization that must take place between sunspot-maxima and sunspot-minima is of the order of from 50 to 60 per cent. APPLETON points out that this variation necessitates a corresponding energy-change in the extreme ultra-violet of the solar spectrum of from 120 to 150 per cent. This reemphasizes the importance of systematic ultra-violet measurements over continents and, wherever possible, in oceanic areas.

This somewhat general discussion could be profitably extended but it is believed that enough has been stated to exhibit the growing importance of the whole field of cosmic-terrestrial relationships and that such a field must become an integral part of the exploration of geophysics on a global scale.

APPENDIX M--REPORT OF SPECIAL COMMITTEE ON PRECISE SURVEYS AND MAPS, 1943-44

C. H. Swick, Chairman

Frank S. Borden	R. B. Montgomery	O. W. Swainson
W. H. Bucher	J. W. Peoples	E. H. Vestine
Carroll F. Merriam		

At the Annual Meeting last year a resolution was passed in which the Section of Geodesy recommended to the Executive Committee of the Union the appointment of a Special Committee on Precise Surveys and Maps, with members from each of the Sections. The resolution was approved by the Union and the appointment of the Committee was authorized by the Executive Committee at its meeting of November 20, 1943. President LOWDERMILK appointed the Committee on March 18, 1944.

As stated in the resolution, the purpose of the Committee is as follows: (a) Survey of technical and scientific procedures in the field of surveying and mapping; (b) promotion of a sustained program of scientific investigation and research for improvement of these procedures; (c) an investigation of the possibility of improvement in the coordination of operations by different agencies and in the greater standardization of the resulting products; and (d) an inquiry into the surveying and mapping needs of the member Sections in planning and executing postwar projects.

The Committee has very little to report this year because of the short interval of time since its formation. We hope by another year to accomplish enough to justify a report at least, and perhaps enough to warrant our continued existence. At present, we wish to let you know that such a Committee exists and to solicit your support and cooperation. If you have any suggestions, or if you have any special needs along the lines of surveying and mapping, please get in touch with any of the members of the Committee.

One item of interest has come to the attention of the Committee. A comprehensive list of definitions of geodetic terms, or what might be called a dictionary of geodesy, has recently been completed in preliminary form by H. C. MITCHELL of the United States Coast and Geodetic Survey. This work was started several years ago by a committee of the Federal Board of Surveys and Maps. When that organization was terminated, the work on definitions was taken over by the Division of Geodesy of the United States Coast and Geodetic Survey. It has all been done under the direction of Mr. MITCHELL, first as Chairman of the Committee of the Board of Surveys and Maps and later as a member of the Division of Geodesy of the Survey. It is hoped that the preliminary draft of the definitions can be photoprinted and submitted to a number of expert geodesists for criticism before the final draft is printed.

APPENDIX N-a--MINUTES OF THE ANNUAL MEETING OF 1944, SECTION OF GEODESY, AMERICAN GEOPHYSICAL UNION

The Annual Meeting was held in Room 202, Hall of Government, George Washington University, Washington, D. C., on June 2, 1944. The meeting was called to order at $09^h\ 15^m$ by the President, R. M. WILSON. (For attendance see Appendix A.)

The reading of the minutes of the Twenty-Fourth Annual Meeting held on April 24, 1943, was dispensed with, since they had been published in the Transactions of 1943 and no corrections or additions had been received.

C. H. SWICK reported on the formation of the new Special Committee on Precise Surveys and Maps. The detailed report of the formation of this Committee is included in the report of the general business meeting of the Union itself.

C. L. GARNER, Chairman of the Sub-Committee on Finance for this Section, gave a general report of his collections for the Special Fund.

J. A. DUERKSEN, Member of the Committee on Membership, urged the Members of Geodesy to invite their associates in the field of geodesy, who are not Members already, to become Members of the Union.

W. D. LAMBERT, Chairman of the Committee to Consider the Establishment of an International Journal of Geodesy, reported that the Committee had not advanced very far as yet. The financial angle was one of the chief obstacles.

The report of the Nominating Committee [F. W. HOUGH (Chairman), C. B. WATTS, and C. H. SWICK] was given by Mr. HOUGH. W. D. SUTCLIFFE was nominated for President and PHILIP KISSAM for Vice-President of the Section for a three-year term beginning July 1, 1944. A motion was made that the nominations be closed and that the Secretary cast a unanimous ballot for Mr. SUTCLIFFE as President and for Mr. KISSAM as Vice-President. The ballot was cast.

The Committee on Resolutions [E. L. HAIN (Chairman), C. J. CLIFFORD, and L. V. JUDSON], Mr. CLIFFORD reporting, presented a Resolution on Accurate Time-Service (see p. 324 for form as passed by the Union), which was unanimously adopted for recommendation to the Union.

The business meeting was closed and the Section proceeded to hear the following scientific papers which are given on pages 219 to 263 of these Transactions:

(1) JOHN BOWIE, JR., Triangulation along the Alaska Military Highway (by title).
(2) AUSTIN E. JONES, A plane map from a sphere by double projection; presented by D. A. RICE; discussed by GARNER.
(3) C. A. WHITTEN, Rapid method for determining astronomical azimuths; discussed by HOUGH, LAMBERT, STETSON.
(4) ARTHUR BUTTERFIELD, Transference of levels by water-surface on Lake Champlain during June and September, 1941; discussed by GARNER, MERRIAM, WILSON.
(5) H. W. HEMPLE, Recent progress of geodetic surveys of the Coast and Geodetic Survey; discussed by GARNER, O'KEEFE, STETSON, SWICK.
(6) J. L. SPEERT, The zenith camera for geographic location; discussed by FUECHSEL, SHNEIDEROV, STETSON, SWICK.
(7) T. A. JAGGAR, A desirable graphical zenith air-navigation instrument; presented by J. L. SPEERT; discussed by JOHNSTON, WHITTEN, WILLIS, WILSON.
(8) GEORGE P. WOOLLARD, Gravity observations in northern New England; read by W. T. THOM, JR.; discussed by LAMBERT.
(9) MANUEL MEDINA, Progreso de los Trabajos Geodesicos y Topograficos en Mexico, de Marzo de 1943 a la fecha (Progress of the geodetic and topographic work in Mexico from March, 1943, to date); translated and read by F. W. DARLING.
(10) A. J. SHNEIDEROV, New service of geodesy; discussed by O'KEEFE.

J. A. DUERKSEN, Secretary

APPENDIX N-b--MINUTES OF THE ANNUAL MEETING OF 1944, SECTION OF SEISMOLOGY, AMERICAN GEOPHYSICAL UNION

The Annual Meeting was called to order by the President, H. E. McCOMB, at $09^h\ 15^m$, June 2, 1944, in the Hall of Government, George Washington University, Washington, D. C. (For attendance, see Appendix A.)

The minutes of the previous meeting having been published and no objections or corrections received, the President declared them approved.

The President welcomed the Eastern Section of the Seismological Society of America, which was meeting jointly with the Section of Seismology, and called attention to the session to be held on June 3, 1944, at Georgetown University.

The Nominating Committee, consisting of Rev. J. B. MACELWANE, S.J. (Chairman), FRANK WENNER, and R. R. BODLE, presented its nominations for President and Vice-President as follows: President, Rev. V. C. STECHSCHULTE, S.J.; Vice-President, FRANK NEUMANN. These were unanimously elected.

The Committee on Resolutions, consisting of FRANK NEUMANN (Chairman), Rev. F. W. SOHON, S.J., and A. C. CHICK, presented three resolutions, on Accurate Time-Service, on Microseismic Phenomena, and on Cooperation between Nations of the Western Hemisphere in Seismology. They were unanimously adopted and referred to the Committee on Resolutions of the Union (see pp. 323-324 for the resolutions as adopted by the Union).

The Section voted to express its thanks and appreciation for the efficient service of the retiring President and Vice-President.

There being no further business, the meeting proceeded to the scientific papers in joint session with the Eastern Section of the Seismological Society of America. This joint session was adjourned at $12^h\ 05^m$, and resumed on Saturday, June 3, 1944, after the business session of the Eastern Section of the Seismological Society of America, finally adjourning at $12^h\ 30^m$, June 3, 1944. (The scientific papers are printed in pp. 267-318 of these Transactions.)

ARCHIE BLAKE, Secretary

APPENDIX N-b1--MINUTES OF THE SEVENTEENTH ANNUAL MEETING OF THE EASTERN SECTION OF THE SEISMOLOGICAL SOCIETY OF AMERICA, WASHINGTON, D. C., JUNE 3, 1944

The Eastern Section of the Seismological Society of America held its Seventeenth Annual Meeting jointly with the Section of Seismology of the American Geophysical Union at Georgetown University, Washington, D. C., June 3, 1944. The meeting was called to order by the Chairman, Dr. W. A. LYNCH, at $09^h\ 30^m$.

Father F. W. SOHON, S.J., presented Rev. L. C. GORMAN, S.J., President of Georgetown University, who welcomed the group on behalf of the University.

The minutes of the Sixteenth Annual Meeting were approved as published. The Chairman called attention to the fact that due to the present world crisis no meetings of the Section were held in 1942 and 1943.

J. B. MACELWANE, S.J., Chairman of the Nominating Committee, submitted the following nominees as officers for the coming year: Dr. W. A. LYNCH, fifth member of the Executive Committee; Commander O. W. SWAINSON, Chairman; FLORENCE ROBERTSON, Vice-Chairman; L. M. MURPHY, Secretary; Dr. J. T. WILSON, Treasurer. There were no other nominations from the floor. The motion was made and carried that the Secretary be instructed to record a unanimous vote for the officers nominated.

Dr. VINCENT DILLON was appointed as Auditor of the Treasurer's accounts. In the absence of the Treasurer, Dr. DILLON read the Treasurer's report. The report was accepted as read. The Auditor promised to present his report as soon as the vouchers were received from the Treasurer's office.

Professor WM. T. McNIFF, of Fordham University, Chairman of the Membership Committee, presented a report of the new Members. He called attention to the fact that applications for Membership Cards were now available and suggested that the present Members keep some available for use when the occasion arose. The Membership Committee has been gratifyingly active during the past year.

FRANK NEUMANN, Chairman of the Resolutions Committee, proposed that two votes of thanks be extended: (1) To our host, Georgetown University, for hospitality; (2) to A. K. LUDY, who has resigned because of ill health as Editor of the Notes. Mr. NEUMANN was instructed to prepare and to transmit these resolutions.

The meeting was then devoted to the presentation of eight scientific papers as follows:

(1) WILLIAM A. LYNCH and VINCENT DILLON, Characteristics of Alaskan earthquake records at distances of 40° to 70° (10 minutes).
(2) A. J. SHNEIDEROV, Earthquakes on the expanding Earth (15 minutes).
(3) E. J. WALTER, An extension of the method of numerical integration of seismograms to include a third integration.
(4) FRANK NEUMANN, Period-amplitude analyses of strong-motion records (15 minutes).
(5) FRANK NEUMANN and H. E. McCOMB, A general-purpose vibration-meter (15 minutes).
(6) FLORENCE ROBERTSON, A mathematical analysis of numerical integration of electromagnetic seismograms (15 minutes).
(7) FRED KELLER, An electronic earthquake-recorder (15 minutes).
(8) H. E. McCOMB, DAVID WARK, and R. E. GEBHARDT, The seismological installation at the South Dakota State School of Mines and Technology, Rapid City, South Dakota (15 minutes).

After the discussion the meeting adjourned to the south lawn of the Georgetown Campus for a picnic luncheon prepared by the wives of Washington seismologists. We wish to take this opportunity of thanking our hosts and hostesses for a most delightful luncheon.

FLORENCE ROBERTSON, Secretary

APPENDIX N-c--MINUTES OF THE ANNUAL MEETING OF 1944, SECTION OF METEOROLOGY, AMERICAN GEOPHYSICAL UNION

The Twenty-Fifth Annual Meeting of the Section of Meteorology was held June 1 and 2, 1944, in three sessions from $09^h\ 15^m$ to $12^h\ 15^m$ and $14^h\ 00^m$ to $16^h\ 30^m$, June 1, and $14^h\ 40^m$ to $17^h\ 00^m$, June 2, President THORNTHWAITE, presiding, in Room 101, Hall of Government, George Washington University. About 150 Members and guests were present (for registered attendance, see Appendix A).

The reading of the minutes of the previous meeting was dispensed with as they had already been published in the Transactions of 1943, and no corrections or additions had been received.

The Committee on Nominations [R. T. ZOCH (Chairman), O. H. GISH, J. C. OWEN] nominated for officers for the three-year period beginning July 1, 1944, F. W. REICHELDERFER for President, H. R. BYERS for Vice-President, and H. D. HARRADON for Secretary. No other nominations were made and these candidates were duly elected.

The Committee on Resolutions [C. F. BROOKS (Chairman) and DELBERT M. LITTLE) reported that no resolutions had been presented for action.

L. P. HARRISON, member of the Committee on Membership representing the Section of Meteorology, urged the Members of the Section to cooperate in obtaining new Members from the large number of qualified persons who have not yet joined the Union. He also called attention to the body of young students interested in meteorology who would be qualified for Associate Membership.

President THORNTHWAITE called attention to the proposal that the Section's Research Committee on Climatology be made a Joint Committee with the American Meteorological Society and stated that the Executive Committee would take it under consideration at its next meeting.

The Secretary mentioned the Research Committee on Extended Forecasts, recently appointed by President THORNTHWAITE. Its composition is as follows: J. NAMIAS (Chairman); R. G. ELLIOTT; H. W. NORTON; C.-G. ROSSBY; and H. C. WILLETT.

The scientific program consisted of 27 papers and reports. Because of difficulties of travel arising from the war, several of the authors living far from Washington were unable to give their contributions in person and, as far as possible, their papers were presented by others. Six papers were read by title. Papers and reports are printed in Part III of the Union's Transactions for 1944.

H. D. HARRADON, Secretary

APPENDIX N-d--MINUTES OF THE ANNUAL MEETING OF 1944, SECTION OF TERRESTRIAL MAGNETISM AND ELECTRICITY, AMERICAN GEOPHYSICAL UNION

The Twenty-Fifth Annual Meeting of the Section of Terrestrial Magnetism and Electricity was held in Room 203, Hall of Government, George Washington University, on June 1, 1944. President E. A. ECKHARDT called the meeting to order at $09^h\ 10^m$ (for registered attendance, see Appendix A).

The reading of the minutes of the last meeting was dispensed with as they had already been published in the Transactions of 1943. No corrections having been received, they were declared approved as printed.

The report of the Nominating Committee [O. H. GISH (Chairman), O. W. SWAINSON, and J. H. SWARTZ] was read by President ECKHARDT in the absence of any members of the Committee. The following nominations were submitted for officers of the Section of Terrestrial Magnetism and Electricity for the three-year period beginning July 1, 1944: President, H. F. JOHNSTON; Vice-President, IRWIN ROMAN; Secretary, DAVID G. KNAPP. It was moved and seconded that the report be accepted, that the nominations be closed, and that the Secretary be instructed to cast a unanimous ballot for the candidates. The motion was carried and the President declared the nominees elected.

The following report was presented by the Chairman of the Committee on Units: The Committee now consists of the following five persons: H. H. HOWE (Chairman); F. C. FARNHAM; H. T. STETSON; E. H. VESTINE; and FRANK WENNER. As a result, in part, of the press of other duties connected with the war, the Committee has not deliberated sufficiently to make definite recommendations upon all of the subjects which have come before it. It is therefore requested that the life of the Committee be extended another year. The Committee urges that the Section recommend that geophysicists follow the practice, already adopted by International action of certain other scientists, of using "gauss" as the unit of flux-density and "oersted" as the unit of magnetic field-intensity. It is, however, recognized that the flux-density in gauss is numerically equal to the intensity in oersteds, within practical limits of measurement, for measurements in air. Therefore, it is not necessary that geophysicists in general take into account which quantity their instruments measure, since when one is measured the other is known. However, in giving results, either the intensity should be stated in oersteds or the flux-density should be stated in gauss; expressions such as "the vertical intensity was 0.555 gauss" should be avoided, as being contrary to International action.

A motion to discharge the Committee with thanks and without prejudice until after the conclusion of the war was lost. The President interpreted this action to be an indication of the intent of the Section to extend the life of the Committee on Units, and he therefore declared it extended until the next meeting of the Section.

A motion was made and seconded to instruct the Committee on Resolutions to prepare a resolution regarding the use of the terms "gauss" and "oersted" based on the Report of the Committee on Units. The motion was carried.

The Chairman of the Committee on Resolutions presented a Resolution on Establishment of a Geophysical Station at the University of Alaska. This resolution was adopted by the Section and passed on to the Committee on Resolutions of the Union (see p. 323 for resolution in final form as adopted by the Union). A second resolution, pertaining to nomenclature, was submitted. Subsequent discussion indicated a strong feeling on the part of the Section that further consideration was required to act intelligently on this resolution. A motion was made and seconded to table this resolution. The motion was carried.

There being no further business, the Section proceeded to the scientific program, and the papers published in Part IV of these Transactions were presented. The meeting adjourned at $12^h\ 00^m$.

J. W. JOYCE, Secretary

APPENDIX N-e--MINUTES OF THE ANNUAL MEETING OF 1944, SECTION OF OCEANOGRAPHY, AMERICAN GEOPHYSICAL UNION

The Annual Meeting of the Section of Oceanography was held in Room 202, Hall of Government, George Washington University, June 1, 1944. In the absence of President WHITNEY and Vice-President SVERDRUP, the meeting was called to order by Secretary SCHMITT at $14^h\ 08^m$ (for registered attendance, see Appendix A).

L. P. DISNEY was requested to serve as Acting Secretary. The reading of the minutes of the previous meeting were dispensed with as they had been published in the Transactions of 1943, and no corrections or additions had been received.

H. A. MARMER, Chairman of the Nominating Committee, presented the following nominations for officers to serve for the period July 1, 1944, to June 30, 1947: For President, H. U. SVERDRUP; for Vice-President, W. L. SCHMITT; for Secretary, L. P. DISNEY. It was moved and seconded that the nominations be declared closed and that the Secretary be instructed to cast a unanimous ballot for the nominees. The motion was carried and the Acting President declared the nominees elected.

Resolutions were presented regarding the continuation of the Oceanographic Unit as a permanent section of the United States Hydrographic Office and the undertaking of extensive bathymetric studies of the Pacific Ocean by the United States Hydrographic Office. Following some discussion, the resolutions as presented were approved by the Section and transmitted to the Committee on Resolutions of the Union for adoption by the Union. The Union combined the two resolutions into one Resolution on Proposed Oceanographic Work by the United States Hydrographic Office (see pp. 323-324).

The scientific program consisted of six papers, two of which were read by title. The papers are printed in Part IV of these Transactions.

The meeting was adjourned at $15^h\ 30^m$.

L. P. DISNEY, Acting Secretary

APPENDIX N-f--MINUTES OF THE ANNUAL MEETING OF 1944, SECTION OF VOLCANOLOGY, AMERICAN GEOPHYSICAL UNION

The Annual Meeting of the Section of Volcanology was called to order by President A. F. BUDDINGTON at $09^h\ 15^m$ in Room 203, Hall of Government, George Washington University, Washington, D. C. (for registered attendance, see Appendix A).

The minutes of the previous meeting were approved as published in the Transactions of 1943.

The Acting Secretary, on behalf of the Nominating Committee [J. W. PEOPLES (Chairman), H. M. BANNERMAN, and EARL INGERSON], presented the following nominations for officers to serve for the period July 1, 1944 to June 30, 1947: President, RICHARD E. FULLER; Vice-President, HOWEL WILLIAMS; Secretary, FRANCIS G. WELLS. It was moved and seconded that nominations be closed and that the Secretary be instructed to cast a unanimous ballot for the nominees. The motion was carried and the President declared the nominees elected.

The Acting Secretary called attention to the business session and urged Members to attend.

The scientific papers were presented as published in Part IV of these Transactions. The papers by TRASK, WHITE, and BODLE were illustrated by lantern-slides, most of which were in color. GRATON asked MILTON about the location of the pre-Paricutín lava. WHITE'S paper was discussed by GRATON and ZIES, and WHITE replied to questions. BODLE'S paper was discussed by McNISH, HOYLMAN, and ZIES. The meeting adjourned at $11^h\ 30^m$.

JOE WEBB PEOPLES, Acting Secretary

APPENDIX N-g--MINUTES OF THE ANNUAL MEETING OF 1944, SECTION OF HYDROLOGY, AMERICAN GEOPHYSICAL UNION

The annual business meeting of the Section of Hydrology was called to order at $09^h\ 15^m$, June 1, 1944, by President CHURCH. A report on the activities of the Committee on Membership of the Union was presented by WALDO E. SMITH, of the Committee. W. G. HOYT reported on progress of the work of the Sub-Committee on Finance. President CHURCH presented his report for the past year (printed in Part V of these Transactions).

Following adjournment of the business meeting, the first scientific session was held. Four papers and the reports of four Research-Committees were submitted as follows:

MERRILL BERNARD reported as Chairman of the Research-Committee on Precipitation.

D. B. KRIMGOLD presented his paper "A suggested method of reporting rainfall-records" followed by formal discussion by A. K. SHOWALTER read by Mr. BRONCA of the Weather Bureau. There were also brief discussions by MERRILL BERNARD and others.

Dr. CHURCH presented a report as Chairman of the Research-Committee on Snow.

Paper by W. U. GARSTKA, "Hydrology of small watersheds, etc." was presented by a representative of the Soil Conservation Service.

Papers Nos. 3 and 4, "The average length of the season with snow-cover, etc." by R. G. STONE and "Some recharge and discharge phenomena, etc." by A. R. CROFT were read by title.

Report R-3 by F. E. MATTHES, "Report of the Research-Committee on Glaciers" was read by W. G. HOYT who, to save time, also read his report R-13, "Report of the Research-Committee on Runoff."

The meeting adjourned at 12^h.

The second session was called to order at $14^h\ 00^m$ by N. C. GROVER as Chairman. Ten papers and the reports of eight Research-Committees were presented as follows:

Report R-4 by H. G. WILM, "Report of the Research-Committee on Evaporation and Transpiration" was read by Dr. HURSH of the Forest Service.

Paper No. 5 by BROOKS and BERGGREN, "Remarks on turbulent transfer across planes, etc." was presented by A. A. KALINSKE, who also presented a brief discussion.

G. W. MUSGRAVE presented report R-5 for Research-Committee on Infiltration.

Paper No. 6 by M. R. HUBERTY, "Soil compaction in cultivated soils" was presented by title.

Report R-6 by VEIHMEYER for Research-Committee on Physics of Soil-Moisture, R-7 by L. J. STRAUB for Research-Committee on Dynamics of Streams, and paper No. 7 by E. W. LANE, "A new method of sediment transportation" were presented by title.

Paper No. 28 by F. R. DREIBILBIS, "A summary of soil moisture, etc." was presented by Mr. SLATER, Soil Conservation Service; discussion by H. L. COOK was presented by title.

Paper No. 8 by JOHNSON and MINAKER, "Sediment movement, etc." was presented by J. W. JOHNSON and discussed by C. B. BROWN.

Paper No. 9 by J. W. JOHNSON, "Rectangular artificial roughness, etc." was presented by Mr. JOHNSON and discussed by R. W. POWELL.

Report R-8 by S. T. HARDING for Research-Committee on Lakes, was read by N. C. GROVER.

Report R-9 by S. W. LOHMAN for Research-Committee on Ground-Water, was presented by W. B. LANGBEIN.

Paper No. 10, "A graphic procedure in the geochemical interpretation of water-analyses" by A. M. PIPER was presented by O. E. MEINZER, who also briefed the discussions by R. A. HILL, C. S. HOWARD, and W. F. LANGELIER.

Paper No. 11 by C. E. JACOB, "Correlation of ground-water levels, etc." was presented by Mr. JACOB who also presented paper No. 12 by L. K. WENZEL and R. G. KAZMANN concerning well-discharge.

Report R-10 by C. S. HOWARD for Research-Committee on Chemistry of Natural Waters, was presented by title.

Paper No. 13 by S. K. LOVE, "Cation exchange in ground-water contamination, etc." was presented by Mr. LOHR of the Geological Survey; discussion by O. C. MAGISTAD, who also briefed the discussion.

Dr. W. C. LOWDERMILK presented report R-11 for Research-Committee on Erosion, accompanied by colored slides showing erosion-conditions in the Yellow River Basin, China.

The session adjourned at 17^h.

The third session was called to order at $09^h\ 05^m$, June 2, 1944, by MERRILL BERNARD as Chairman. Twelve papers, the report of one Research-Committee, and the report of one Sub-Committee were presented as follows:

Report R-12 by R. E. HORTON for Special Committee on Hydrologic Regions, was read by W. G. HOYT.

H. G. WILM presented report of the Sub-Committee on Runoff of Subsurface Flow.

Paper No. 14 by G. H. KEULEGAN, "Spatially variable discharge, etc." was presented by C. F. IZZARD. Discussion by W. W. HORNER was by title.

Paper No. 15 by C. F. IZZARD, "The surface profile of overland flow, etc." was presented by Mr. IZZARD. Discussion by W. W. HORNER was by title.

Paper No. 16 by WALDO E. SMITH, "Hydrologic behavior of small agricultural watersheds" was presented by title.

Paper No. 17 by M. D. HOOVER, "Effects of cutting forest vegetation, etc." was presented by Dr. HURSH.

Paper No. 18 by C. C. McDONALD, "Forecasting spring runoff from snow-surveys, etc." and discussion by JOHN SALO were presented by PHILLIP LIGHT of the United States Weather Bureau.

Paper No. 19 by G. K. WOOD, "Accuracy of stream-flow records" was presented by Mr. BENNISON of the United States Geological Survey.

Paper No. 20, "Evaluation of runoff distribution values, etc." was presented by Mr. JETTER with discussion by GORDON WILLIAMS.

Paper No. 21 by LENZ and SAWYER, "Estimation of stream-flow from alkalinity determinations" was presented by Mr. LENZ who also presented discussion by STIEMKE.

Paper No. 22 by A. T. LENZ, "Checking runoff, etc." was presented by Mr. LENZ and discussed in person by W. B. LANGBEIN.

Paper No. 23 by C. O. CLARK, "Flood-storage accounting" was presented by Mr. CLARK and discussed in person by ERNEST SCHULEEN.

Paper No. 24 by MAX KOHLER, "A new forecasting technique, etc." was presented by Mr. KOHLER and discussed in person by F. F. SNYDER.

Paper No. 26 by C. S. JARVIS, "River discharge in Brazil" was presented by Mr. JARVIS.

The minutes of the meeting of the Executive Committee held on May 30 relate in part to paper No. 25 by R. E. HORTON, "Some hydrologic characteristics of the United States, Part 1." (See Part V of these Transactions for minutes of this meeting.)

Two resolutions [Resolutions on Postwar Work in Geophysics and of Thanks to Major PETER W. RAINIER (see p. 323 for final form as adopted by the Union)] were presented by the Committee on Resolutions consisting of R. W. DAVENPORT (Chairman), O. E. MEINZER, and WALDO E. SMITH; these were adopted and transmitted to the Committee on Resolutions of the Union for consideration.

A recommendation regarding procedure or handling and presenting resolutions was also offered by the Committee. This recommendation was approved and transmitted for consideration by the Union at its business meeting. The communication submitted to the Union is as follows:

The report of the American Geophysical Union's Special Committee on Resolutions at the Twenty-Fourth Annual Meeting of 1943 contains the following statement: "The present method of handling and presenting resolutions is by no means satisfactory. The Committee on Resolutions does not have adequate time to consider, compare, collate, and combine the various resolutions handed to it by the Secretaries of the Sections and others; furthermore, the Union, as a whole, has no adequate opportunity for discussion before taking action. It is respectfully suggested that the question of a modification of the present procedure be placed on the agenda of a meeting of the Executive Committee in time to have such modification, if approved, take effect at the next Annual Meeting of the Union."

The Section of Hydrology recommends to the Union that some action be taken to implement the foregoing statement in order that the deliberations of the Committee on Resolutions of the Union and of the several Sections may be conducted under less pressure and haste, with more opportunity for communication with the officers, Chairmen of Committees, and Members of the Union, and in order that this function of the consideration and presentation of resolutions may be performed in an adequate and effective way.

The following action is recommended by the Section of Hydrology for consideration:

(1) That the Union's Committee on Resolutions be made a Standing Committee, appointed at the same time that the other Committees of the Union are appointed, in order that it may function throughout the year and especially in advance of the annual meeting.

(2) That each Section be urged to appoint a similar Standing Committee on Resolutions.
(3) That the preliminary announcements of the Annual Meetings of the Union include an invitation to the Officers and Members of the Union to make suggestions as to desirable resolutions to the Committee on Resolutions of the Union or to the Committee on Resolutions of the appropriate Section.

The Secretary of the Section was instructed to send the greetings of the Section, with hopes for speedy and lasting recovery, to LELAND K. WENZEL, Chairman of the Committee on Publications of the Section.

The session adjourned at noon.

For registered attendance at the three scientific sessions, ranging from 50 to 75, see Appendix A.

The fourth session was called to order at 14^h, June 2, 1944, by W. G. HOYT as Chairman. The business meeting of the whole Union did not adjourn until after $14^h\ 30^m$. Time, therefore, did not permit having a round-table discussion. In lieu thereof the Chairman introduced O. E. MEINZER to an audience of well over 100. Dr. MEINZER spoke briefly on work of American hydrologists relating to water-supplies for war-activities and at 15^h introduced Major PETER W. RAINIER, who gave most interesting remarks on experience in developing water-supplies for the British Army in North Africa. Major RAINIER talked for about 45 minutes followed by fully 15 minutes of questions and answers. President CHURCH was able to absent himself long enough from the meeting of the Executive Committee of the Union to thank Major RAINIER at the close of his talk and to adjourn the meeting as a whole at $16^h\ 15^m$.

W. G. HOYT, Acting Secretary

APPENDIX N-h--MINUTES OF THE ANNUAL MEETING OF 1944, SECTION OF TECTONOPHYSICS, AMERICAN GEOPHYSICAL UNION

The Annual Meeting of the Section of Tectonophysics was held in the Hall of Government, George Washington University, on June 1, 1944. The meeting was called to order in Room 202 by President ERNST CLOOS at $09^h\ 17^m$. The minutes of the previous meeting were approved as printed in the Transactions of 1943.

The Chairman urged that all manuscripts be submitted before June 15, 1944, in order not to delay publication of the Transactions. It was pointed out that through error last year's officers were listed in the printed program of the Twenty-Fifth Annual Meeting.

The scientific papers were then presented as published in Part IV of these Transactions. GUNN'S paper was discussed by THOM and NADAI. INGERSON'S paper was discussed by Mrs. KNOPF and the Chairman. ANDERSON'S paper was discussed by INGERSON, Mrs. KNOPF, McKINSTRY, and the Chairman. NADAI showed a very interesting motion-picture in which the formation of slip-surfaces in metals could be watched. The development of the patterns was photographed very clearly by having the surfaces coated with a brittle white paint before the metals were deformed. The paper was discussed by LOUGHLIN, McKINSTRY, and Mrs. KNOPF.

Presentation and discussion of the first four papers required considerably longer than the scheduled time, so it was decided to adjourn for lunch and have the remaining papers presented in the afternoon. The morning meeting adjourned at $12^h\ 15^m$.

The afternoon session was held in Room 203 and was called to order at $14^h\ 00^m$ by President CLOOS. FELLOWS' paper, in the absence of the author, was presented by the Chairman, Vice-President NETTLETON presiding. It was discussed by INGERSON. The one by CLOOS, which followed BROUGHTON'S paper, was discussed by NADAI and INGERSON. NETTLETON presented the paper prepared by him and ELKINS; it was discussed by CLOOS.

The meeting adjourned at $15^h\ 44^m$.

EARL INGERSON, Acting Secretary

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AMERICAN GEOPHYSICAL UNION

TWENTY-FIFTH ANNUAL MEETING

PART III

SECTION OF METEOROLOGY

REPORTS AND PAPERS

Washington, D. C.
June 1, 1944

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TRAINING PROGRAM IN METEOROLOGY FOR LATIN-AMERICAN STUDENTS

Charles F. Sarle

The primary objectives of the Training Program in Meteorology for Latin-American students were threefold:

(1) To accelerate the development of meteorological sciences in the countries south of the Rio Grande, which, in turn, would benefit weather service in the United States.
(2) To increase the safety of flying in Latin America, particularly for citizens of the United States.
(3) To contribute to the economic development of the countries of Latin America, to the extent that weather information, past, present, and future, can be utilized in planning and operating agriculture, industry, and other economic enterprises.

The program provided (1) for the training of nearly 200 weather observers at the subprofessional level, and (2) for training 40 of these observers in professional meteorology at the American universities (now engaged in training military weather officers) along with a limited internship in forecast offices of the Weather Bureau.

The first phase of the program was carried out during February 22 to September 15, 1943, in cooperation with the University of Antioquia at Medellín, Colombia, South America. Medellín is a city of about 175,000 people located in a beautiful mountain valley of the Andes. The "Inter-American Meteorological School" as it was called, provided instruction in observational work, the installation and care of weather instruments, meteorology, map plotting, map analysis, mathematics, physics, and the English language to Spanish, Portuguese, and French-speaking students from 20 Latin-American Republics [see 1 of "Notes" at end of paper]. The number of students selected from each country varied from two from Paraguay to 37 from Brazil.

There was a total of ten American instructors, including the Director, EDWARD H. MARX of the United States Weather Bureau; six of these were technical and four were English instructors. There were ten Latin-American instructors, eight technical and two in mathematics. The ten Latin-American instructors were from the following countries [see 2]: Argentina, 2; Brazil, 2; Chile, 1; Colombia, 2 (in mathematics); Ecuador, 1; Guatemala, 1; and Uruguay, 1. At first, a major part of the instruction, both lectures and laboratory, was given in Spanish and Portuguese. However, the latter part of the course was largely in English, due to a demand on the part of the students who had made rapid progress in their understanding of English.

The problem of organizing a course, with students speaking three different native languages and with a highly variable command of English, at a school in a foreign country that had to be improvised, including even the furniture, and with instrumental equipment and supplies that had to be transported several thousand miles across enemy submarine-infested waters, as well as by air, presented many serious difficulties. One of the factors that contributed most to the success of the school in Medellín was the very fortunate selection of the students.

The men selected as students had to meet two basic scholastic requirements: (1) A knowledge of physics and mathematics, or at least show an aptitude for study of physical science; and (2) a knowledge of English or an aptitude for learning languages. The latter was particularly essential from the standpoint of selecting students for advanced meteorological training in the United States on the completion of the course in Medellín. Selection on the basis of school records did not appear feasible as scholastic standards of each country are different, and, furthermore, an evaluation of the courses of study even within each of 20 countries would be extremely difficult.

In order to secure objectivity in the selection process, the United States Civil Service Commission [3] was asked to design a battery of four tests composed of multiple choice items to be translated into Spanish, Portuguese, and French. Test (1) was in mathematics and physics; test (2) was in English; test (3) was a language-aptitude test; and test (4) was a physical-science aptitude test. These tests were given by representatives of the State Department in each of the 20 countries and the papers were sent to Washington where they were promptly graded by the Civil Service Commission. Local Cultural Relations Committees had already screened the numerous applicants and

had made out "interview" forms for those who were allowed to take the two-day test. Approximately 800 persons took the examination. From this number, about 200 were selected, partly on the basis of the showing made on the examination and partly from the information contained in the interview form. Men already employed in meteorology or aviation or who were strongly recommended by the local Cultural Relations Committees were selected, provided they made a reasonable showing in the examination and about 25 per cent from each country were selected from the "top of the register". The students chosen by this process materially exceeded our expectations, especially from the standpoint of cooperativeness, industry, and genuine interest in meteorology.

The students and school were well received by the people of Medellín. Living accommodations were arranged for the students and instructors in "pensiones" or boarding houses and some of the student-groups rented furnished homes and employed a cook to prepare their meals. When Vice-President WALLACE visited the class on Good Friday, the President of the Student Council, Señor JOSE OSCAR DIEZ MARTINEZ, from Mexico, presented him with a beautiful parchment scroll that all the students had signed.

Early in August, 1943 [4], 40 students from 19 countries were selected from the class for advanced training in meteorology in the United States and six were selected to study agricultural climatology and statistical methods at Iowa State College [5]. These selections were made on the basis of student performance in the class at Medellín with special emphasis on the competence of their work in mathematics, physics, English, and meteorology, and on their industry and opportunity for obtaining employment in meteorology in their respective countries. The largest number selected from any one country was ten from Brazil. The 12 best-qualified students were assigned--three each to the California Institute of Technology, New York University, Massachusetts Institute of Technology, and the University of Chicago--for classes beginning October 4. The remaining 28 were assigned to the University of California at Los Angeles for additional pre-meteorological training for the class beginning December 13. However, 12 of these men were able to enter and continue with the class at the University of California which began October 4.

Of the 24 Latin-American students who will complete the course on June 5, 1944, 16 will be assigned to various forecast offices of the Bureau as internes until about September 1, 1944, when they will return to their own countries. Eight of the students who have come from tropical countries (from countries from which two or more students were selected) will be assigned to an advanced class beginning June 19 at the Institute of Tropical Meteorology of the University of Puerto Rico. The remaining 15 students at the University of California at Los Angeles will complete their course in August and be assigned as trainees to Weather Bureau forecast stations for a few weeks before they return to their respective countries.

Although many of these students had a language handicap and in some instances wholly inadequate training (but aptitude) in mathematics and physics prior to entering the Medellín class, they were able to "hold their own" in competition with especially trained and selected United States students assigned to the universities for training as weather officers for the Armed Forces. Several have made outstanding scholastic records and all will return home with an enthusiasm for, and an interest in, meteorology that argues well for the fulfillment of the primary objectives of the program.

Notes

[1] Funds for the School were provided jointly by the Office of the Coordinator of Inter-American Affairs and the Defense Supplies Corporation, with the understanding that the Weather Bureau would administer the project and contribute certain personnel and instruments. Active assistance was also rendered by the Division of Cultural Relations of the State Department. Offices, class rooms, and library facilities were provided without expense in the Law School by the University of Antioquia, Medellín.

[2] The Latin-American instructors and their countries were as follows:

Argentina: JOSE MARIA FRAGA, Second Chief, Division of Meteorology, Argentina Service of Meteorology and Hydrology; instructor in physics, instruments, and observations. ANGEL PAPETTI, Division of Meteorology, Argentina Service of Meteorology and Hydrology; instructor in weather-map analysis.

Brazil: DURVAL CALHEIROS GOMES, Chief of the Instruments Division, Meteorological Service of Brazil; instructor on instruments and observations. ALCIDES B. de MENDOCA LIMA, instructor in meteorology, map-construction, and observations.

Chile: ERIC TROLLUND, Meteorological Service of Chile; instructor in meteorology, observations, and instruments.

Colombia: LUCIO CHIQUITO CAICEDO, Civil Engineer in the Public Works Department of Medellín; instructor in mathematics. JORGE MEJIA RAMIREZ, Professor of Mathematics in the National School of Mines of Medellín, Colombia; instructor in mathematics.
Ecuador: LUIS E. MENA, Meteorological Service of Ecuador; instructor in instruments and pilot-balloon observations.
Guatemala: JOSE VASSAUX PALOMO, Meteorological Service of Guatemala; instructor in meteorology, instruments, and observations.
Uruguay: SEBASTIAN E. VIEIRA, Meteorological Service of Uruguay; instructor in meteorology, instruments, and observations.

[3] A Report on scholarship examinations given in Latin-American Countries for the selection of students to be trained in meteorology, by ALBERT V. CARLIN, United States Weather Bureau, and FREDERIC M. LORD, United States Civil Service Commission, Educational and Psychological Measurement, v. 4, No. 1, pp. 69-74, Spring Issue, 1944

[4] Funds for the advanced training and internship in meteorology were appropriated to the State Department by Congress for the fiscal year 1944. The program is being administered by the Weather Bureau. The five universities, New York University, Massachusetts Institute of Technology, University of Chicago, California Institute of Technology, and the University of California at Los Angeles, contributed 16 tuition scholarships.

[5] The training for the six students in agricultural climatology was financed in three ways: (A) Subsistence by the Division of Cultural Relations of the State Department; (B) tuition by Iowa State College; (C) travel by the individual students. The students in climatology will have two months' internship in Weather Bureau centers upon the completion of their courses in June, 1944.

U. S. Weather Bureau,
Washington, D. C.

PRELIMINARY REPORT OF RESEARCH COMMITTEE ON CLIMATOLOGY

A. E. Parr

The Research Committee on Climatology of the Section of Meteorology was appointed in 1943. Shortly after its establishment the Chairman, H. Landsberg, was obliged to resign because of work in connection with the war. In his place A. E. Parr was appointed, but, for various reasons, no meeting of the members could be called in time for making a formal report at the twenty-fifth annual meeting.

Besides encouraging research of a high quality for increasing existing knowledge of climatology, the aim of the Committee will be to cooperate with investigators in other fields where problems involving climatological interpretation are required. Several inquiries and letters expressing interest in the work of the Committee have been received.

Membership of the Committee is now as follows: Alfonso Contreras Arias; Phil E. Church; W. C. Jacobs; Helmut Landsberg; J. B. Leighly; A. E. Parr (Chairman); F. W. Reichelderfer; A. K. Showalter; R. G. Stone; C. W. Thornthwaite; and H. G. Wilm.

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A DEW-POINT APPARATUS FOR USE IN AGRICULTURAL CLIMATOLOGY

A. G. Dinaburg

In connection with a study of the development and survival of the free-living stages of sheep roundworm parasites under natural conditions, it became necessary to determine the relationship between the relative humidity of their environment and the viability of the preparasitic stages. Since this involved the measurement of the humidity of a small volume of stationary air in a closed container, the dew-point method was adopted. As is well known, it is difficult with this method to decide visually when the dew is first deposited. Consequently, the following method of determining the dew-point objectively was developed.

The apparatus used (see Fig. 1) is basically similar to that described by THORNTHWAITE and OWEN [see 1 of "References" at end of paper]. The mirror on which the dew is deposited is

made by polishing and silverplating part of a flat, thin, copper bar. A copper-constantan thermocouple junction is then soldered to the face opposite the silvered position, followed by a small piece of copper bar, to insure good thermal contact. The final size of the mirror is 8 by 8 mm. The remainder of the bar is bent into a U-shape with unequal limbs. The short limb, containing the mirror, passes through a cork stopper; on the cross-limb, an electrical heating-element is wound, while the long limb is for immersion in a cooling medium of ice and water. By means of the ice-bath, and the heating element controlled by a rheostat, the mirror can be brought to any desired temperature, which is measured with thermocouples and potentiometer. The formation of dew on the mirror is detected by a self-generating, photronic cell, and a galvanometer having a sensitivity of 7×10^{-4} microampere per mm.

The arrangement of the apparatus, as shown in Figure 1, is as follows. The mirror, held by the cork in the sample tube, is placed in the beam of light from the lamp, so that a beam four mm in diameter is reflected at an angle of about 25° on the central disc of the photocell. This disc is not light sensitive and absorbs most of the light that is reflected regularly by the mirror. When the mirror is cooled to the dew-point, water condenses on it and scatters the light from the mirror on to the light sensitive portion of the photocell. This increases the output of the cell, the increase being indicated by the galvanometer.

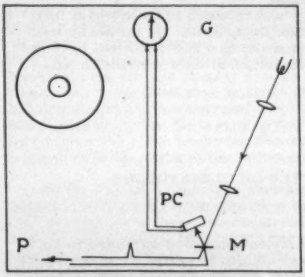

Fig. 1--Schematic arrangement of parts of dew-point apparatus (light from lamp reflected by mirror M on to photocell PC; output of photocell measured by galvanometer G; temperature of mirror measured by thermocouples and potentiometer P; front view of photocell with central light insensitive disc shown by large circle)

After this arrangement was worked out, the writer discovered a paper by MOSS [2] in which the intensity-distribution of light scattered from a dew-covered mirror was given. His data showed that most of the light leaves the mirror within about 4°.5 to 22°.5 on either side of the optical axis. By calculation it was found that the central disc of the photocell subtended a total angle of about 13°, thus intercepting the most intense portion of the scattered light. Consequently, another disc five mm in diameter was placed on the cell-window between the disc and rim to subtend an angle of 9°, blocking the directly reflected beam as before. This arrangement increased the sensitivity of the photocell to the light scattered by the dew.

To determine the dew-point, the temperature of the mirror is lowered slowly until an increase in the output of the photocell indicates the formation of dew. Then the temperature of the mirror is raised slightly by means of the heater.

As the temperature rises from below to above the dew-point, the condensation of water on the mirror is changed to evaporation from the mirror. The temperature at which the transition from one process to the other occurs is the dew-point, and is indicated by the galvanometer as the turning-point from increasing to decreasing output by the photocell. It is advisable to keep the temperature of the mirror not far below the dew-point for a short period, otherwise the heavy accumulation of dew on the mirror may interfere with the exchange of heat between mirror and dew.

The relative humidity above the surface of various test-solutions was measured as follows: About ten cc of distilled water or of saturated solution of KNO_3, NaCl, or $Mg(NO_3)2$ were put into a number of 50 cc test-tubes, which were stoppered and kept at room-temperature overnight. The dew-point of each sample was determined, and the relative humidity calculated, using either the temperature of the solution or of the room as the reference-temperature. Measurements on six samples of each of the four solutions showed an average relative humidity of 99.8 per cent (range 99.4 to 100 per cent) over the distilled water, 93.1 per cent, with a range from 92.6 to 93.6 per cent over KNO_3; 75.5 per cent (range 75.3 to 75.8 per cent) over NaCl, and 53.1 per cent (range 53.0 to 53.4 per cent) over $Mg(NO_3)2$. For comparison, there are the data given by THORNTHWAITE and HOLZMAN [3] in their Table 1, for KNO_3, 94+ per cent, for NaCl, 75 per cent, for $Mg(NO_3)2$, 52 per cent. Their data are good within ±1 per cent.

Since the present temperature-measurements, made with a Leeds and Northrup "Student" potentiometer, are good to 0°.1 C, the final relative-humidity figures may vary from about ± 0.2 per cent to ± 0.7 per cent. However, since the output of the photocell shows a large change with a

small temperature-change near the dew-point, it should be possible to obtain more precise data by the present method by using a more sensitive potentiometer and with good control of the ambient temperature.

One of the climatological uses which suggests itself for this instrument is the more accurate measurement of the humidity of large air-masses as in greenhouses. Another is the measurement of the humidity of small volumes of stationary air which form the microclimate of a particular sample of material, as in the case of soils, fertilizers, or feces harboring parasites, or in samples of a more extensive microclimate, as in the case of various layers of air adjacent to the soil.

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A DESCRIPTIVE GRAPH OF CLIMATE

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Due to the many elements contributing to formation of climate and the diversity of interests affected, a quantitative description of it is very difficult to make for general purposes. Even a descriptive classification is not complete and is not satisfactory for the reason that it must necessarily be long and involved. Yet the importance of climate demands some type of analysis, and some means of comparison of climates at various regions is necessary.

Such attempts of classification of climate that have been made are based primarily on its two most important elements, namely, precipitation and temperature, with some account being taken of the variability of those two items. These two factors, however, do not give a complete picture since such elements as winds, types of storms, humidity, cloudiness and fogginess, and other minor items are not considered. Nevertheless, two well-known systems of classification have been based primarily on these two elements: The KOEPPEN system [see 1, 3, 4 of "References" at end of paper] and THORNTHWAITE'S system [6] which includes also the effect of evaporation. Other elements may be used for comparing climates for special purposes. Thus, SINGER [5] presented a climatogram based on temperature and relative humidity to show variations in climate from the standpoint of human health.

The same two elements, temperature and precipitation, have been used as a basis of a descriptive graph of climate. This graph is not a classification or a quantitative description but is designed merely to give a pictorial representation of climate at any given point where data are available in so far as the climate can be depicted in terms of temperature and precipitation. This graph is formed by plotting the mean monthly data of temperature as ordinates against precipitation as abscissas as it may be seen in Figures 1 to 4.

The graph classifies temperature into six classes and precipitation into five classes into which the points fall when plotted. The monthly and seasonal variations are shown by the plotting. The months are designated by Roman numerals as January, I, to December, XII, but these numerals are shown completely for only one graph, that is, for Valdivia, Chile, on Figure 1. In general, only the numbers of the first and twelfth months and the months of a conspicuous point such as July are shown on the graph.

The six classes of temperature are designated as follows:

Hot: Where the mean monthly temperatures exceed 80° F.
Warm: Where the mean monthly temperatures are 65° to 80° F.
Mild: Where the mean monthly temperatures are 50° to 65° F.
Cool: Where the mean monthly temperatures are 32° to 50° F.
Cold: Where the mean monthly temperatures are 0° to 32° F.
Frigid: Where the mean monthly temperatures are entirely below zero.

These temperature designations are the same that were used by DEASY [2].

The limits of temperature have been selected to be consistent, as far as may be possible, with a few natural points which mark a significant temperature for life or to be consistent, as far as possible, with other investigators of climate. The lowest classification, "frigid", gives the upper limit as zero on the Fahrenheit scale. This is selected primarily because of its significance on the Fahrenheit scale which is in wide usage in many countries. It was used by DEASY in his temperature-graph. This point would be equivalent to -15.5 C.

The upper limit of the second class, "cold", is 32° F, or 0° C, and is selected because it is the freezing-point of water and is, therefore, a critical point for all forms of life. It is utilized by DEASY and is included in KOEPPEN'S system, as described by LANDSBERG [4], to define the E or polar classification. ACKERMANN [1] says that 0° C is a better limit for various agricultural and vegetational boundaries than -3.0 C, used by KOEPPEN [4] as the lower limit of the C-climate. The difference, however, is not material.

The upper limit of the third class, "cool", 50° F, corresponds to the upper limit of the E-class in the KOEPPEN system and is approximately the lowest temperature for human comfort. It was also used by DEASY as the upper limit of his "cool" class.

The next point, 65° F, is the upper limit of the "mild" class. It corresponds approximately to 18° C, the lower limit of the A-class in the KOEPPEN system in which it represents the lowest temperature at which tropical vegetation will thrive. DEASY used 68° F for his corresponding limit but the difference is not considered of material importance.

From 65° to 80° F is the "warm" class. The upper limit was selected on the basis of data given by FINCH and TREWARTHA [3] as a mean temperature of the tropical rain-forest regions. It was also used by DEASY for the upper limit of his "warm" class.

The five classes of precipitation are as follows: Arid, being the driest; semi-arid; subhumid; humid; and wet. These designations of precipitation have no fixed numerical values but vary with the temperature to take into account the effect of evaporation. They are shown, therefore, by straight sloping lines.

The limits of the classes of precipitation are based on the climatic classification of THORNTHWAITE [6], and a brief description of his system is needed to explain the derivation of these limits. THORNTHWAITE'S classification is based primarily upon precipitation as may be seen from the manner in which the limitation of his precipitation-evaporation index parallels the isohyetals of the mean annual precipitation over the United States. For this reason, it was considered to furnish the best basis of the limits of precipitation on this chart.

In order to formulate his classification, THORNTHWAITE studied the data of precipitation from some 1,100 stations in the United States, and established an empirical relationship called "precipitation-evaporation ratio" for the mean monthly values. This relationship was expressed by the equation

$$P/E = 11.5\,(P)^{10/9}/(T - 10)$$

in which P is precipitation, E is evaporation, and T is temperature. The sum of the (P/E)-ratios of the 12 months makes the (P/E)-index (I) except that, in order to eliminate decimals, the sum was multiplied by ten. The annual (P/E)-index is then expressed as

$$I = \sum_{n=0}^{n=12} 115\,(P)^{10/9}/(T - 10)$$

This index should be used only with a minimum temperature of 28°.4 F, which point is based on the demands of plant-life. Dr. THORNTHWAITE emphasizes that I is the summary of the monthly ratios. However, the equation has been used herein with the mean annual temperatures and mean average monthly precipitation--that is, mean annual precipitation divided by 12. Except as modified by the exponents (10/9), the means could properly be used since this is the only factor deviating from a straight-line relationship. Since this exponent does not make a great change, it was considered that the errors arising from using monthly averages would not be too great when the indefinite limits of the classes are considered.

The values of the index I range from zero upward and are divided into five classes corresponding to as many humidity provinces which are as follows:

Designation Symbol	Name	Type of vegetation	Value
A	Wet	Rain-forest	128 and up
B	Humid	Forest	64-127
C	Humid	Grass-land	32-63
D	Semi-arid	Steppe	16-31
E	Arid	Desert	Less than 16

In a similar study made of temperature which was classified to conform to the precipitation-provinces, THORNTHWAITE developed a factor which he called "thermal-efficiency factor" that was expressed by the formula

$$i = (t - 32)/4$$

where i is the monthly thermal-efficiency factor. Five temperature-provinces with a separate designation of a zero-value were developed to correspond with the similar classes of precipitation. These provinces are as follows:

Temperature-province Symbol	Name	Value	Temperature-province Symbol	Name	Value
A′	Tropical	128 and up	D′	Taigo	16-31
B′	Microthermal	64-127	E′	Tundra	1-15
C′	Mesothermal	32-63	F′	Frost	0

To compute the values for the class-limits of the precipitation, the values of the above index were inserted in the formula for the thermal-efficiency factor. To obtain the minimum value of the temperature, 1.0 was inserted in the formula and the value of T = 32°.4 F was obtained. For the maximum temperature, 128 was inserted in the formula and the value for temperature of 83°.2 F was obtained.

Using these limits for temperature with the above formula of (P/E)-index, I, and substituting values of 128 and 1.0, the limiting values of the classes for precipitation were computed. The computed values to determine the limits of the precipitation-classes are given in the following tabulation:

Class	Temperatures °F	°C	Precipitation in	mm
Arid	32.4	0.2	0.32	8.13
	83.2	28.4	1.03	26.16
Semiarid	32.4	0.2	0.59	15.73
	83.2	28.4	1.93	49.02
Subhumid	32.4	0.2	1.10	27.94
	83.2	28.4	3.60	91.44
Humid	32.4	0.2	2.05	52.07
	83.2	28.4	6.73	170.94
Wet	All above humid			

The study for the climatic graph was made on the basis of temperature as expressed by °F and of precipitation measured in inches, and the examples shown in the Figures hereinafter are based on those systems of measurement. However, similar climate graphs can be made by using other units of temperature and precipitation. The above Table includes the same values expressed in °C and precipitation in mm.

The four Figures are designed to illustrate sufficient array of all types of climate. The legend on each Figure gives the source of the data, the station at which they were obtained, and the KOEPPEN classification of climate.

In Figure 1, the tropical rain-forest climate, which has a high mean annual temperature and is well-watered the year round, is illustrated by the data of Georgetown, British Guiana. The hot desert-type is shown by Jacobabad, India. The mesothermal, cool climate of the steppe-type is illustrated by Pocatello, Idaho, United States of America. A humid, mesothermal, continental climate having warm humid summers and cool humid winters is illustrated by Kansas City, United States of America. The cold polar climate is illustrated by Upernivik, Greenland, while Valdivia, Chile, represents another mesothermal climate that is found on the west coast in the latitudes of the prevailing westerly winds.

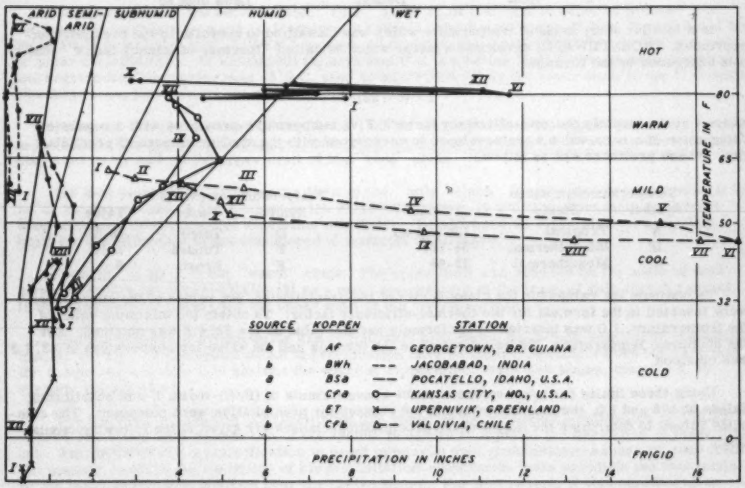

Fig. 1--Types of tropical rain-forest, hot-desert, mesothermal, and cold-polar climates

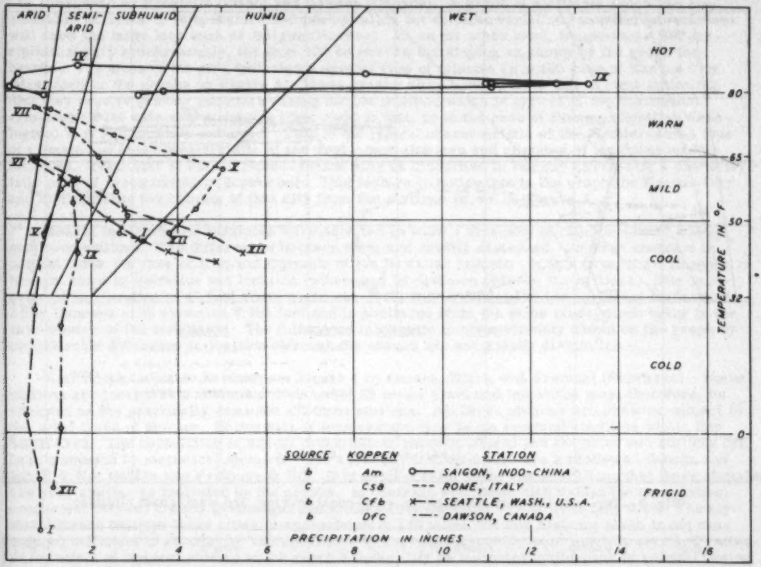

Fig. 2--Types of tropical, Mediterranean, west-coast, and mesothermal climates

Figure 2 shows different varieties of a similar range in climate. A tropical climate shown by Saigon, Indo-China, represents the monsoon which is shown by the wide range in monthly rainfall. The well-known Mediterranean climate having hot, dry summers and mild humid or wet winters is illustrated by Rome, Italy. The west-coast climate as found in the northern latitudes is represented by Seattle, Washington, United States of America. A cold mesothermal climate having a rather uniform annual distribution of precipitation but a wide variation in temperature is represented by Dawson, Canada.

Two types of low-latitude ocean climate are illustrated in Figure 3 by Hilo and Humuula, Territory of Hawaii. Hilo is on the seacoast and is exposed to the northeast trade-winds while Humuula, on the same island, is at a higher elevation. Boston represents a typical east-coast marine climate with a uniform distribution of precipitation and moderate range of temperature. Bergen, Norway, shows a west-coast climate in the high latitudes.

The three stations, Omaha, Blair, and Fremont, Nebraska, United States of America, on Figure 4 have very similar climate which is the middle-latitude, continental type with warm, humid summers and cool, relatively dry winters.

Certain characteristics of the graphs are important indications of types and features of climate. Location shows the general type, that is, whether it is hot or cold, dry or wet. Hot climates are located near the top, cold at the bottom; while the wet climates are on the right and the dry are on the left. Hot, dry desert climates are located on the extreme upper left-hand corner. The graphs for tropical rain-forest regions lie nearly horizontal and close to the 80° line. Other definite climatic types are represented by their typical locations. The shape of the graph is likewise indicative of climatic types. A long narrow graph with a horizontal axis indicates uniform temperature and a wide variation in precipitation. A narrow graph with a vertical axis indicates large variation in temperature and small variation in precipitation. These latter

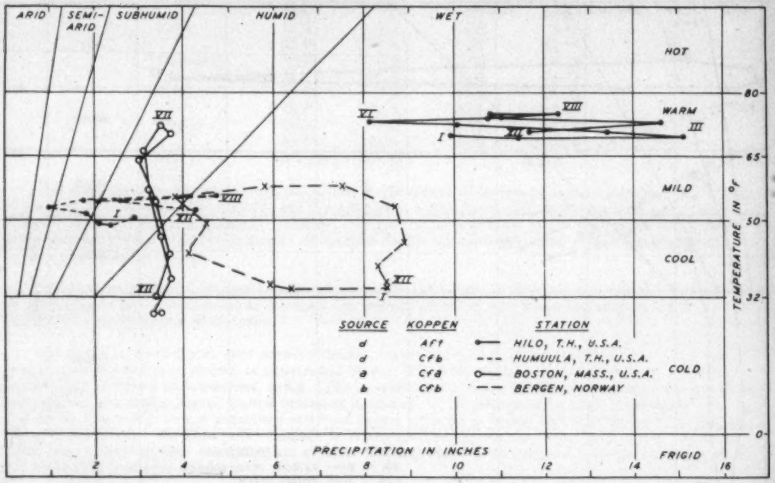

Fig. 3--Types of low-latitude oceanic, east-coast marine, and west-coast climates

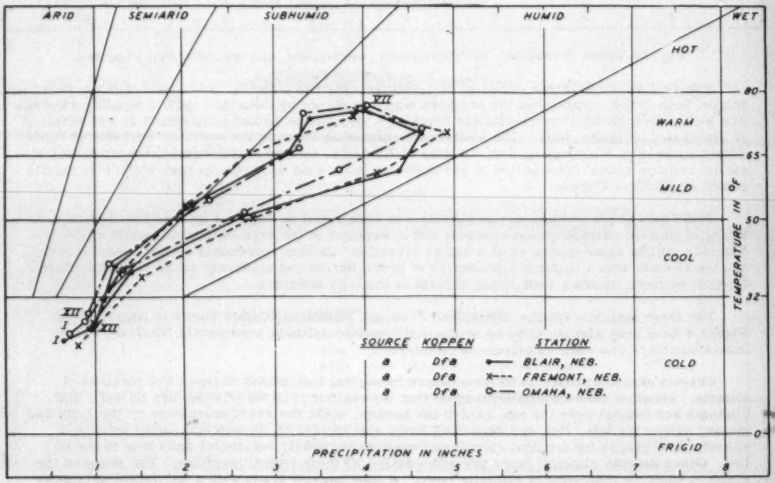

Fig. 4--Types of middle-latitude continental climates

are illustrated by Pocatello (Idaho) and Dawson (Canada). A graph of a climate which has considerable variation in temperature and precipitation but with the variations in different seasons will show the large loop such as Bergen (Norway). If, on the other hand, temperature and precipitation vary synchronously, the loop will be narrow but sloping as shown by the graph for Seattle. The slope of the axis indicates a special type of climate as in the case of Kansas City (Missouri) or the graphs on Figure 4. These graphs slope upward from left to right indicating that they receive greater moisture during the hot months, which is typical of the continental climates. If the axis slopes upward from right to left, as in the case of Rome or Seattle (Washington), a dry summer is indicated. This is the typical characteristic of the Mediterranean type of climate and also characteristic of the west-coast climates and climates of the lower middle latitudes. The effect of the hurricane-season may be discerned in regions affected by a characteristic peak of precipitation in September. This feature is noticeable in the graph for Kansas City and distinguishes the climate of that city from the stations shown on Figure 4.

Most of the foregoing examples were selected to show a diversity of climate among widely scattered stations. The differences between them are readily discerned. Another contrast is pointed out in the case of Hilo and Humuula of the Hawaiian Islands. In this case, the difference is brought about by elevation and location rather than by distance between the stations. Hilo is located at an elevation of 40 feet above mean sea-level and is exposed to the northeast trade-winds while Humuula is at elevation 6,685 feet and is sheltered from the same trade-winds being in the rain-shadow of the mountains. The difference in climate is conspicuously shown on the graph by considerable difference in location although the shapes are not greatly dissimilar.

Similarity of climate is shown on Figure 4 by Omaha, Blair, and Fremont (Nebraska). These stations are located at a maximum distance of 32 miles apart and insolation may, therefore, be accepted as the practically same for all three stations. All three stations are likewise subject to the same types of storms. Uniformity of temperature may be an accepted condition within this small area. The correlation of annual precipitation between Omaha and the other two stations has been computed by statistical methods. The correlation-coefficients are as follows: Omaha and Blair, 0.712; Omaha and Fremont, 0.702. It is evident from these considerations that these climates are very similar as indicated by the graphs. In contrast with these high values the correlation-coefficient between Omaha (Nebraska) and Kansas City (Missouri) [Fig. 1] is only 0.28. The air-line distance between these cities is approximately 170 miles but this distance alone is not considered sufficient to account for the difference in correlation-coefficients which is ascribed rather to the effect of tropical storms which reach Kansas City as indicated by the peak of rainfall during September.

This graph does not pretend to give a descriptive formula for any climate nor does it measure climate by a numerical value. It can give an approximate pictorial comparison of various climates and for this purpose it is hoped that it will prove useful.

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CLIMATE AND HIGHWAYS

Hans F. Winterkorn

Fifteen years ago, Professor ENO of Ohio presented to the Highway Research Board a paper on "The influence of climate on the building, maintenance, and use of roads in the United States." The following subheadings indicate the scope of Professor ENO'S report: (1) Temperature; (2) frost; (3) sunshine; (4) wind; (5) humidity; (6) precipitation; (7) runoff; (8) evaporation; (9) application of the data to highway activities; and (10) further lines of research. Professor ENO treated these topics in an excellent manner, and the author sees no need for repeating his work, except possibly to bring the information up to date.

Besides coordinating the then available information, Professor ENO made out the following list of needed research:

(1) The depth to which frost penetrates the soil in various localities over the country should be determined.
(2) The relation of frost-depth to the length and the severity of the cold-weather season or spell should be sought.

(3) The influence of various covers to prevent deep freezing should be tried out (especially covers of adjacent road-shoulders).
(4) Runoff-data have been widely taken, but a condensed volume of the best data should be compiled and a concise statement regarding the various formulas made.
(5) Further research into the field of evaporation and of percolation should be made.
(6) The actual effect in reduced labor-efficiency, and number of defects caused by the influence of these various factors upon labor, should be studied.
(7) Determination of the best means of determining the field-percolation value of any given soil, etc.

Undoubtedly great progress has been made along the suggested lines of research during the past 15 years. It would be a worthy and intriguing task to fit the present available knowledge into the framework set up by Professor ENO [see 1 of "References" at end of paper]. A symposium on the general topic of climate and highways planned for the next meeting of the Highway Research Board may be expected to bring forth much of this type of information.

For this and other reasons it has been decided to present here a general formulation of the problem of durability of highway-structures exposed to climatic forces. It is hoped that this treatment may serve as a theoretical guide in the analysis of the large bulk of data which are being and will be accumulated by the different highway- and airport-agencies on this important problem.

It is well recognized by the highway engineer that climatic agents are responsible to a great extent for the destruction of our highways. However, very little is known concerning the actual mechanism of destruction. Thus, while water is recognized as the chief enemy of highway-pavements and highway-bases, cases are on record of roads continuously saturated with water which have stood up well, while roads through deserts have failed because of water-action even though the distance from the water-table was rather great and precipitation negligible. It is for such reasons that the highway engineer recognizes on one hand the importance of climate, but on the other hand feels rather at a loss to put his finger on just what happens. It is for this reason that the present approach of attempting to give mechanisms of the action of climate on roads appears justified.

Highways and airports are generally considered to consist of three parts, that is, the subgrade or underlying soil, the base, and the surface. Often the base and the surface are represented by one structure; for instance, in the case of a concrete pavement which is laid directly on the subgrade. These three parts in unison give a road its stability, that is, its ability to carry traffic under all occurring conditions of temperature and moisture. While the structural parts of different roads or airports may vary markedly in physical and chemical properties, they all must possess internal friction and/or cohesion. Internal friction is usually designated as that part of the shear-resistance which is directly proportioned to the normal pressure on the shearing-plane. Cohesion is usually defined as that part of the shear-resistance which is more or less independent of the normal pressure or which is a complex function of the latter. Formalistically, one may conceive of the cohesion as being a type of friction produced by molecular attraction or internal pressure. From this point of view, the total shear-resistance would be a product of (internal pressure + applied pressure) × coefficient of friction. Both the cohesion and the friction in a system vary greatly with the density of the system, and climate affects its shear-resistance mainly by its loosening effect. This concept of friction and cohesion determining the stability of a soil or a pavement leads to the simplification of the theoretical picture to the extent that whether the system considered be a soil-material, or a bituminous pavement, or a Portland-cement-concrete pavement, one deals with mineral aggregate which is bound together by a cementing agent, be it bitumen, or Portland cement, or any other binder. In loosening up such a system, climate must weaken and overcome the cohesion of the system, or in the case of a cohesionless material it must overcome the confining pressure. One of the problems involved in the destructive action of climate on a cohesive system is illustrated simply by the phenomena occurring if a clay-clod is immersed in water. If the clod be moist it may be found to resist indefinitely the action of water. However, if dried out and then immersed in water, it will probably slake in a few minutes. Repeated wetting and drying is often used in the laboratory to break down large clods of very cohesive clay. In conformance with this illustration the central thesis of this paper is as follows.

The destructive action of climate on highway-structures is not so much a function of the average moisture- and temperature-levels, but rather of the fluctuations of temperature and moisture occurring in the structures as a result of climatic influences. Of course, the average temperature- and moisture-levels cannot be entirely disregarded since they influence especially the speed and location of the equilibrium in the case of chemical reactions which may be involved in the deteriorating process. Evidence for the correctness of this thesis and indications of the

working mechanism of climatic forces are treated subsequently under the following headings: (1) Mechanical stresses set up by temperature-changes; (2) mechanism of water-attack on dry cohesive systems; and (3) the condition of water in porous systems.

Mechanical stresses set up by temperature-changes

Mechanical stresses of shrinkage and expansion set up by temperature-changes have long been recognized as playing an important role in the disintegration of rock and similar rigid materials. Shrinkage-stresses set up due to cooling or to drying out of a concrete slab lead to shrinkage-cracks if the friction between the subgrade and the concrete is greater than the shrinkage-stresses and if the latter are greater than the tensile strength of the concrete. Excessive expansion in hot weather may lead to a blowout in a concrete pavement. A great difference in the thermal-expansion coefficient of the larger sized aggregate and the mortar-matrix leads to popouts of the aggregate, the latter often taking along adhering mortar and other particles. Another effect of temperature-changes which affects the stability of concrete slabs is the downward curling of the edges if the upper part of the pavement has increased in size due to solar heat in daytime, and the upward curling during night-time when the more rapidly cooled upper part has contracted. As a result of this curling the pavement loses locally the supporting power of the subgrade and is more easily broken by heavy loads.

Bituminous pavements being plastic at normal temperature are not as easily damaged by daily temperature-changes as are rigid pavements. Of course, if improperly designed they may get soft and sticky in hot weather. At low temperatures at which the asphaltic cement becomes hard and brittle, shrinkage-cracks may form in a similar way as described for concrete. If those cracks are subsequently filled with deleterious extraneous matter or if they become ports of entrance for water, general deterioration of the pavement may follow. These are just a few examples illustrating deterioration of highways caused by simple changes in temperature. These changes are sufficiently well known so that the principles involved require no further treatment. More complex, and of greater general importance, are those phenomena in which both moisture and temperature are involved.

The mechanism of water-attack on dry cohesive systems

The entrance of water into any porous system is due to the affinity of the water for the internal surface of the system concerned. If this affinity is not present no entrance will take place, irrespective of the surface-tension of the liquid. This is illustrated by the entrance of water into a glass capillary on one hand, with resulting capillary rise and the resistance of mercury to enter a glass capillary for which it has no affinity. If the affinity between the liquid and the capillary wall is greater than the affinity of one molecule of the liquid for another, then the adsorbed film of the liquid may carry along a liquid column to a height which is determined by the surface-tension of the liquid, that is, by its molecular attractive forces. This basic importance of the affinity of the liquid for the surface of the solid must be kept in mind for the proper understanding of all capillary phenomena. In the following discussion such cohesive systems as soil, Portland-cement-concrete, and asphalt-mineral systems shall be briefly considered.

As previously indicated the results of exposure of a soil to water depends upon the moisture-content of the soil, that is, the extent to which the water-affinity has already been satisfied. In general, two main factors appear to govern the consequences of the water-attack: These are the driving force or the affinity of the internal soil-surface for water, and the cohesive forces holding the system together. The relative magnitudes of these forces determine the general reaction. On the other hand, the speed with which the particular reaction occurs depends to a great extent on the permeability of the soil-system, and upon the ease with which free and adsorbed gases may escape from the pore-space. If this escape is prevented, a type of failure may occur which possesses great similarity to an explosion, although of course not liberating so high an amount of energy as is usually associated with this term. The concept that the driving force is the affinity of the internal surface for water makes it easy to understand why certain moist, cohesive systems may be exposed to free water for any length of time without observable change. It is obvious that the affinity for water is satisfied in such systems and that no driving force for the water-attack is left. Depending upon the type of soil considered, its location, and possible confinement, water-attack may result in erosion, in mud-flows, in slides, or in a general loosening up of the soil [2]. In the latter case, the total amount of loosening up depends on the number of wetting and drying cycles the system has undergone. This loosening up, though less dramatic than, for instance, a mud-flow, may result in a very severe decrease of the stability of a subgrade soil, and may lead to a road-failure in the case of flexible pavements or of rigid pavements which do not possess sufficient thickness and beam-strength to distribute the load applied over a large enough area, or to bridge over weak spots.

A system possessing properties intermediate between those of soil and Portland-cement concrete is soil stabilized by means of Portland cement, commonly known as soil-cement. This material is widely used for bases of highways and airports. In the case of soil-cement the cohesion of the system is provided largely by the cementing agent and is of a more permanent character than the cohesion of the natural soil, which is to a large extent a function of its moisture-content. It is commonly assumed that the durability of soil-cement depends upon its resistance to water-attack, and also upon the cohesive strength of the material which resists destruction by the expansive forces of freezing water. In the standard tests for durability, soil-cement samples are submitted to 12 cycles of wetting and drying, and freezing and thawing, respectively, the samples being brushed after each cycle to determine the amount of material which has been loosened up on the surface. It is indicative of the importance of the water-affinity of the internal soil-surface, that in soil-cement under comparable conditions greater cement-contents are required for greater water-affinities, that is, greater clay-content and greater activity of the clay. Also, in the case of clay-soils, faster destruction is experienced as a result of exposure to wetting and drying cycles than of exposure to freezing and thawing cycles. Clearly these tests are intended to imitate climatic action; they also indicate the importance assigned to fluctuations of temperature and moisture-content.

In the case of a properly-designed and well-cured Portland-cement concrete the cohesion of the system is of sufficient magnitude to withstand the forces set up by the water-affinity of its internal surface. Of greatest importance, as far as durability is concerned, is proper density, that is, small pore-space of the system and a small average diameter of the pores. In the case of certain types of aggregate (for example, opal in California) and cements high in alkali, continued presence of water permits attack of the aggregate by the alkali resulting in growth and deterioration of the concrete. Intermediate wetting and drying may stimulate the speed of growth. The underlying mechanism may be pictured as follows [see 3 of "References" at end of paper]:

> "Water acts on the clinker until the resulting gel becomes packed so tightly that no more water can force its way through. The cement or concrete will retain this condition as long as it is immersed in water. If the water is removed by evaporation, the dehydrated gel shrinks and the mass becomes porous. When it is again immersed in water, capillary action carries the water rapidly through the shrunken colloid to the particles of unchanged clinker with the result that additional hydration products are formed. White found that the gel retains this reversibility at atmospheric temperature for at least 20 years."

This evidence again attests to the greater importance of fluctuations in moisture-content as compared with that of the average level of moisture-content, even in such weather-resistant material as Portland-cement concrete.

Scaling of concrete is often observed in cases where snow and ice are removed with the help of such salts as sodium chloride or calcium chloride. This is due to the penetration of these salts into the concrete and their subsequent reaction with components of the latter. This situation can be alleviated or prevented by decreasing the water-affinity of the internal surface of the concrete by means of polar organic substances such as vinsol. The most important single factor as far as durability of a normal concrete is concerned is the impedance to penetration by deleterious aqueous solutions. This impedance depends, as previously indicated, on such mechanical factors as available pore-space and average pore-size, and also on the water-affinity of the internal surface which is an expression of chemical and physico-chemical factors.

In the case of asphalt pavements water-attack may lead to a stripping of the bitumen from the coated aggregates or to a general loosening up of the system resulting in a decrease in mechanical stability. The severity of the attack depends again on the water-affinity and the accessibility of the mineral surfaces in the system. Accordingly, the most dangerous season is the early spring when the normally available water has a chance to enter through fissures in the bituminous films caused by winter brittleness. In the case of a high-type bituminous pavement it is difficult to say whether repeated wetting and drying has a more deteriorating effect than continued exposure to water, as long as all the mineral particles are properly coated with bitumen. In low-type bituminous systems, especially in soil-bitumen where the amount of bituminous material employed is not sufficient to cover the entire internal surface, repeated wetting and drying tends to be much more severe than simple exposure to water.

So far, an attempt has been made to treat the effects of moisture and temperature as separate items. It is obvious that such a separation does not exist in nature, where moisture-changes usually go hand in hand with temperature-changes. This results in a greater complexity of the observed phenomena than has been indicated. An additional important item, perhaps the key for the under-

standing of the outstanding riddles, lies in the complexity of water as a material. This complexity is especially apparent if the water is contained in porous systems possessing hydrophilic internal surfaces.

The condition of water in porous systems [4]

Water is a peculiar substance. It is liquid at normal temperatures while similar compounds with higher molecular weight, for example, H_2S and H_2Te are gaseous in the same range; while in the liquid state water gives x-ray patterns which are indicative of crystalline, that is, solid materials. The melting-point of normal liquids increases with increasing pressure, while that of water decreases first with increasing pressure, and behaves "normally" only at relatively high pressures. The underlying reason for all these phenomena is the architecture and the dipole character of the molecule which permits it to associate with considerable energy with molecules of its own kind. Qualitatively, one might say that water behaves normally only when the externally applied pressure outweighs considerably the inter-molecular attraction. The complexity of water-behavior is indicated by the graph in Figure 1, which represents a simplified picture of the findings of TAMMANN [5] and of BRIDGEMAN, respectively. This picture gives five different modifications of solid water stable at different temperatures and pressures, four of them having corresponding liquid modifications at temperatures above the solid-liquid curve. This picture is rendered even

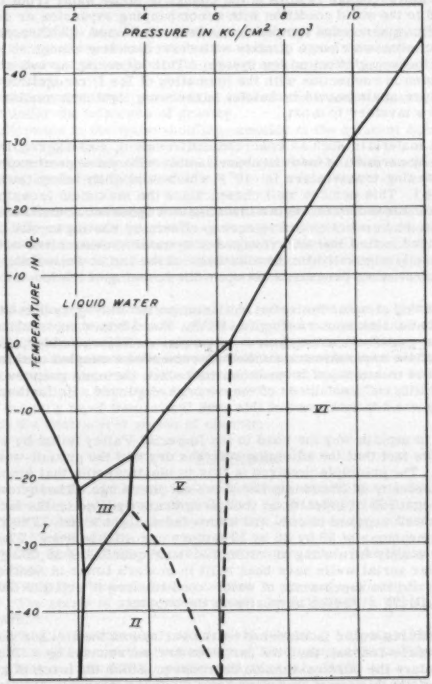

Fig. 1--Phase diagram for one component system H_2O (after Tammann and Bridgeman)

more complex by the existence of hysteresis phenomena and of submodifications such as Ice I', III', etc.

There is considerable evidence that large attraction-pressures exist on the surfaces of mineral materials. While these pressures are probably largely of an electrostatic nature, and as such possible of solution by molecular theoretical analysis, a different approach appears to be more directly useful. The way for such an approach was shown by TAMMANN in explaining the relationship between surface-tension and compressibility of water; for this he employed the concept that internal pressures may be assumed to produce the same type of results as external pressures.

Employment of this concept on the condition of water in porous systems necessitates a knowledge, or at least an estimate, of the attraction-pressures involved. FREUNDLICH [6] calculated from experimental data by GURWITSCH that Fuller's earth adsorbed 183 volume per cent of methylalcohol with an average pressure of from 20,000 to 25,000 atmospheres. There exists sufficient evidence that water is usually more strongly adsorbed on mineral surfaces than methylalcohol. The phase-diagram shows that the melting point of water at a pressure of 25,000 atmospheres is considerably above 50°C.

The conclusion which must be drawn from this evidence is that in a moist, porous system practically every temperature-change results in the change of some water from the solid to the liquid, or from the liquid to the solid condition with accompanying expansion or contraction. At pressures below 2,050 atmospheres and temperatures between 0° and -22°C, contraction occurs upon liquefaction. This continuous change of state with corresponding change in volume cannot help but exert a general loosening effect on the system. This loosening-up has so far been recognized only for the expansion in connection with the formation of Ice I; recognition of its existence over the entire temperature-scale should be helpful in throwing light on a number of phenomena which hitherto have been a mystery to most.

Porous construction materials such as concrete, soil-cement, soil-aggregate, and others often are tested for durability by permitting them to absorb water with subsequent exposure to freezing. The normally adopted freezing-temperature is -10°F which is slightly below the lowest freezing-point of the expansive Ice I. This point is well chosen since the maximum freezing-pressure exists at this point, that is, 2,050 atmospheres. Some investigators ignorant of the theoretical importance of this point have tried to obtain more severe freezing-effects by cooling to still lower temperatures. They were surprised to find that this resulted in a smaller destructive action; this phenomenon, of course, is easily accounted for by shrinkage of the ice at decreasing temperatures resulting in a relief of the expansion-pressures set up in the freezing of Ice I.

In the attempted freezing of some moist but well-compacted clay-gravel mixtures it was found that they do not expand, but shrink upon cooling to -10°F. The obvious explanation for this phenomenon is that the water contained in the system was under such large adsorption-pressures that it fell out of the domain of the expansive Ice I. Well-documented examples of this type are available by the score. Detailed treatment of them is omitted since the main purpose of this discussion is to point out the availability and usefulness of the concept employed. Its further specific application must be left to those who can make use of this tool.

This new tool helps to explain why the road in the Imperial Valley failed by water-accumulation in the subgrade despite the fact that the adjoining soil was dry and the ground-water table a considerable distance away. The principle involved in this is identical with that employed in the "aerial" wells of the Greek city of Theodosia two thousand years ago. These aerial wells consisted of pyramidal aggregations of calcareous rock-fragments erected on the heights overlooking the city where they were well exposed to cold and water-laden night winds. The ruins of these structures possessing dimensions of 30 by 20 by 10 meters can still be seen. These structures represented a city water-supply furnishing an estimated daily quantity of 15,000 gallons for drinking and irrigation. Similar aerial wells have been built in modern times in southern France. The working of an aerial well and the mechanism of water-condensation in soil are described somewhat as follows by L. CHAPTAL [7], a French authority on the subject:

> "At low temperatures water is adsorbed on the surface of the soil (or mineral) particles and held there by surface-tension; thus the particles are surrounded by a thin liquid film. With rise in temperature the surface-tension decreases. Since the force of gravity remains constant the film tends to thicken at the lower position of the mineral particle at the expense of the other parts. When this water accumulation on the lower part is sufficiently large, a drop detaches itself, which, protected from immediate evaporation by the particle above, takes the form of either capillary or free water depending upon the condition of the soil. Thus, the

adsorbed moisture becomes available to plants and represents an actual moisture-gain to the Earth. When the temperature falls, the liberated drop is not available to thicken the adsorbed-water film; instead, a new quantity of atmospheric water-vapor is captured and fixed at the surface of the soil-particles. This theory is confirmed by the fact that in the 'aerial well', all other conditions being equal maximum water-release is observed during the hottest days."

L. CHAPTAL'S theory is, in general, correct; it can be improved by reference to some data obtained by BAVER and WINTERKORN [8]. The latter showed that at a constant water-pressure of 30 mm of mercury, the water-adsorption by Putnam clay decreased from 25 per cent (on the basis of the dry weight of the clay) at 30°C to less than 12 per cent at 40°C, that of bentonite from 33 per cent to less than 14 per cent, and that of Davidson clay from 21 per cent to less than four per cent, for the same temperature-change. While adsorption-data were not obtained for temperatures lower than 30°C, the trend of the moisture-temperature curves indicates that the difference in adsorption-power between 20° and 30°C would be even greater than that between 30° and 40°C. Therefore, a considerable part of the moisture adsorbed and strongly held at lower temperatures becomes free water at elevated temperatures. This free water can then be released in accordance with L. CHAPTAL'S theory.

From the evidence available the following conditions appear to be conducive to good water-collection:

(1) Sufficient aeration to permit the passage of a large volume of air through the collector; however, the aeration should not be too violent, since this causes evaporation-losses.
(2) Low temperature of the collector to permit maximum water-adsorption from either hot or cold humid air.
(3) Sufficient temperature-variation in the collector to change adsorbed into free water which descends under the influence of gravity.
(4) A great difference in the water-holding capacity of the mineral surfaces at the different temperatures obtaining in the structure.
(5) The type of construction and material employed should favor nocturnal radiation and impede heating up during daytime.

It is evident that these conditions are present to a greater or lesser extent in highway-fills and subgrades. Black pavements, warming up rapidly in daytime and cooling rapidly at night, may add the finishing touches to make these systems good water-collectors. For these reasons, the principles working in aerial wells deserve consideration by the highway engineer. The immediate cause for such detrimental water-accumulation is fluctuation of temperature.

The purpose of this paper was to set forth and sustain the thesis that the destructive action of climate on highway pavements and bases is not so much a function of the average moisture- and temperature-levels, but rather of the temperature- and moisture-fluctuations occurring in the respective structures. Because of the wide field under consideration and the lack of time, the treatment had to be rather general, with emphasis on what appeared to be the primary causes involved in the always complex phenomena encountered. It is hoped that the indicated action-mechanisms may not only be of theoretical interest, but may assist the engineer in his never-ceasing battle with the destructive action of climate.

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INTRA-CLOTHING CLIMATE

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It has often been said that man is a product of his environment. From the point of view of the intra-clothing climatologist, this statement is far too simple. Man's thermal well-being at any given moment depends upon at least three environments: The weather of the locality in which he happens to be; the weather which lies between the outermost layer of his clothing and his naked skin surface; and thirdly, what might almost be called the weather of the body itself. Meteorologists and climatologists have studied the first; physiologists have made progress in research on the third; but the second--the personal man-made climate which lies next to every human body--is a recent development of science. From time immemorial clothing has been made by necessity of raw materials at hand, or has been designed to suit convention or satisfy the desire for ornamentation. The importance of studying clothing as a science was hardly realized before the war. Now the exigencies of combat have shifted men from the cold, wet Aluetians to the dry sub-zero center of Greenland, and from the stifling, humid heat of monsoon Burma to desert Iran. Because the war covers the Globe, the problem of protecting the human body has become urgent; and the need for determining climatic phenomena in the intra-clothing layers has become a primary problem of the Quartermaster Corps.

Outer boundary--The outer limits of the zones of intra-clothing climate may be defined as the ambient atmosphere as measured at any point more than a few tenths of an inch beyond the outer surface of the clothing. The properties of the outer environment are determined by analyzing the numerous variables of weather and by man-made shelters or localized environments through which man passes. In this outer region, air-temperatures encountered in nature range from below -90° F to above 134° F, though they may greatly exceed these extremes under artificial conditions.

In this paper consideration will be given only to conditions which occur in nature. Humidity, rain, wind-velocity, solar, sky, and earth radiation each give independent variables which throw stress upon man. In order to simplify all these variables, it is necessary to translate them into one common denominator. This is possible if, instead of taking absolute quantities of heat, one transposes the figures to amounts of heat transferred from or into a unit-area in a given length of time. For this purpose the unit of kg-cal/m^2/hr is convenient because it gives a direct correlation with the usual units of metabolic rates. The atmosphere is the absorber of heat emitted by the body and is only infinitesimally affected by it, except in closed areas, such as tents and crowded rooms.

Inner boundary--The properties of the inner boundary of the intra-clothing climate may be considered in summary to be those of a heated surface regulated to approximately 33° C (91.4 F), even though variable amounts of heat are released from it as a by-product of changing activities of the body. The tissues below the surface of the skin have the ability to alter their conduction in the order of one to four by means of thermostat-like adjustments related to increasing and decreasing blood-flow through, within, and beneath the skin. When simple radiation, conduction, and convection fail to cool the body to the ideal equilibrium, the skin-temperature gradually rises to a normal upper limit of about 36° C (96.9 F). Under these conditions, the moisture in the form of perspiration is exuded onto the surface of the skin, and heat is removed by evaporation. On the other hand, when the surface of the skin cools below 33° C, a level of discomfort is reached at approximately 28° C for the trunk area. At this point, an increase of heat-production, usually in the form of shivering, may arrest the fall of skin-temperature. The extremities, however (with the exception of the head), may continue to lower their surface-temperature until the parts themselves may, eventually, be injured or even destroyed by freezing. To simplify this brief discussion, attention will be confined to the torso only.

This solid inner boundary surface radiates as a 98 per cent perfect black-body. The rate varies between a basic sleeping rate of 40 kg-cal/m^2/hr and an indefinite upper limit of 300 to 600 kg-cal/m^2/hr under conditions of strenuous activity. This inner skin-wall also changes from a relatively dry surface--evaporating only about 12 cc of moisture/m^2/hr, through a relatively dry but vapor-permeable membrane at 28° C--to a totally wet surface which under extreme conditions is provided with over 1,000 cc of moisture/m^2/hr when the skin-temperature rises to normal maximum of approximately 36° C.

Intra-clothing climate-zone--The narrow zone of transition under specific consideration in this paper lies between the body and the atmosphere and has a multiplicity of characteristics all its own. This so-called intra-clothing climate-zone may be reduced to a minimum thickness of about 0.02 inch if the body is naked in a heavy wind, or extended outward by use of clothing until it is several inches thick. Within this narrow zone lies the dynamic adjustment of the outer

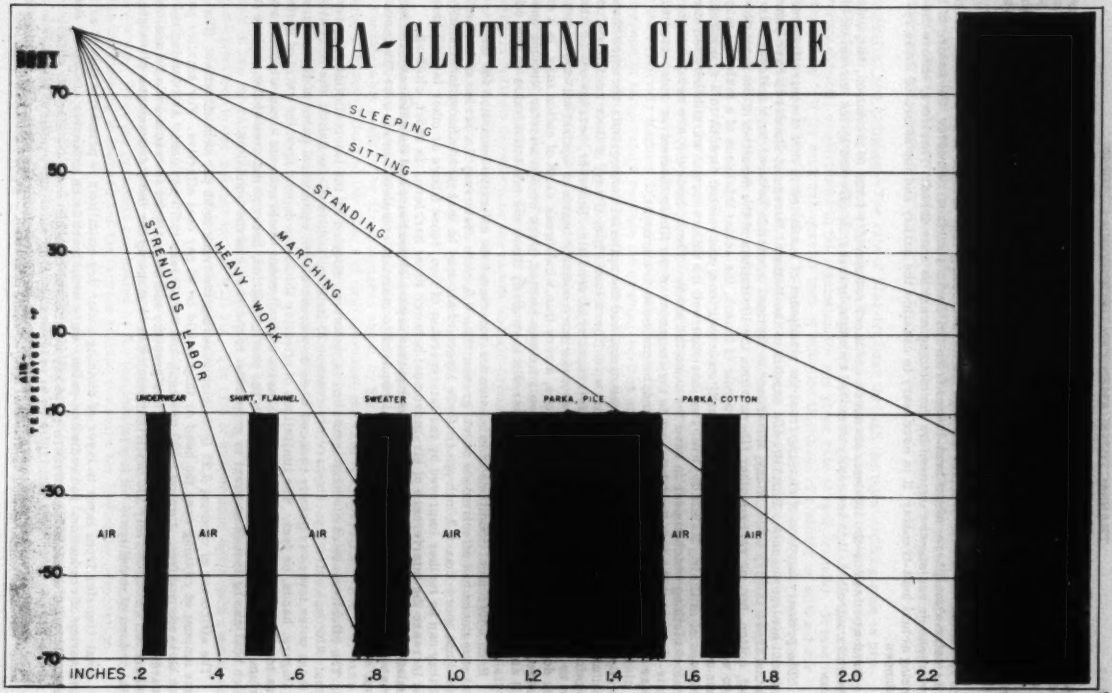
INTRA-CLOTHING CLIMATE
SKIN
70
50
30
10
-10
-30
-50
-70
AIR TEMPERATURE °F
SLEEPING
SITTING
STANDING
MARCHING
HEAVY WORK
STRENUOUS LABOR
UNDERWEAR
SHIRT, FLANNEL
SWEATER
PARKA, PILE
PARKA, COTTON
AIR
INCHES .2
.4
.6
.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2

Fig. 1

atmosphere to that of the body. The variables to be considered in this zone include the number, thickness, and types of material interposed into this space.

As a rule it may be considered that heat must always pass from the body-surface into the environment. The body is not able to accept more heat than it produces except over short periods of time. Continued reversal of the heat-flow would cause fever and would soon become lethal.

The elements of heat-transfer through the intra-clothing zone are the same as those which, in the outer atmosphere, affect heat-losses from the Earth's surface. However, the nature of interruptions or resistances imposed by the clothing must be considered. Therefore, before discussing actual heat-transfer, it is necessary to examine the quality and the nature of these resistances.

Dead air itself is the lightest, cheapest, and most satisfactory form of insulation, but, unless it is well controlled, it is too easily removed by slight breezes, or affected by the movement of man.

The primary function of clothing from the standpoint of insulation is that of controlling convectional air-movements. BARTON and experts of the National Bureau of Standards have pointed out that there is very little, if any, difference in thermal insulation between such materials as wool, cotton, fur, or various other fibers within the limitations of the densities of the material from which most clothes are made. As a rule of thumb, the actual thickness of a material may be taken as a measure of insulation under still air-conditions, and related directly to a comparable thickness of still air. Naturally, everyone has observed the differences in warmth between various items of clothing which appear to have the same thickness. These, however, are related to factors of air-movement through the fabric, or to the character of the fibers themselves under conditions where varying quantities of moisture, wind, or pressure are present.

Cotton, for instance, becomes limp and damp, and the material consequently becomes thinner even under slight pressure; whereas damp wool-fibers lose little, if any, of their resilience, and therefore hold their thickness and their full capacity of dead air. However, because cotton fibers can be more densely packed together, they make more suitable barriers against air-movement than do the kinky fibers of wool. Therefore, a very thin wind-break cloth of cotton may, in a strong breeze, be of much greater insulation than a loosely-knitted, thick woolen sweater, though, under still air-conditions, the thick wool sweater will have many times the insulation value of thin cotton.

Even under ideal conditions of minimum air-movement the effective insulation for unit-thickness never has effectiveness much greater than 0.2 inch. However, if a series of baffles are placed not more than 0.2 inch apart, these layers of air may be increased almost indefinitely, but they can be further improved by the interspersing of fine, loose fibers or other lateral barriers that increase the interference of air-movement between these barriers. In short, clothing-insulation is primarily a process of tying together layers of dead air, and its efficiency can be determined by the lightness of the material required to maintain complete control over the movement of this included air.

The effectiveness of clothing-insulation is, however, affected by the law of diminishing returns. Although extra layers apparently continue to build up additional insulation, the effectiveness of these outer layers is greatly reduced when they cover small, cylindrical parts of the body, such as fingers, hands, or feet. The limitations of effective thickness depend upon the ratio of surface-area to radius. A stove which adequately heats a small room would not heat a vast circular auditorium even if its walls were packed with the best insulation, because the area of the surface from which heat can be lost is so great in proportion to the radius of the insulation.

The efficiency of clothing 0.25 inch thick covering the trunk is 99 per cent effective. The same amount of clothing over the head or thigh would be 95 per cent effective. For smaller parts, such as hands and feet, it drops to 80 per cent, and for fingers to 70 per cent. As clothing increases in thickness these differences grow greater, and soon a point is reached where additional clothing fails to effectively add sufficient insulation to make up for the disadvantages of weight, bulk, or loss of mobility.

Heat-transfer from layer to layer of clothing under dry conditions is primarily that of an infinite series of conduction- and radiation-paths. Only when there is an extensive air-space does the employment of radiation-barriers yield any significant control.

The escape of water-vapor carrying its heat of vaporization from the surface of the body is

for the most part uninhibited by the presence of normal clothing fibers, unless they take the form of a solid membrane impervious to moisture. This means that, under still air-conditions, heat may be removed by evaporation of sweat as readily through a dense wind-proof cloth as through a mosquito-netting of the same thickness. When there is air-movement, however, the fact that masses of moist air may be interchanged with dry air greatly increases evaporative cooling.

Although there are many other variables of lesser importance too numerous to mention here, consideration of the following primary factors concerning the nature of resistances is sufficient to clarify the character of the micro-climatic functions of the intra-clothing zone. Therefore, let us consider the nature of heat-transfer according to the primary avenues of radiation, conduction, convection, and evaporation.

Conduction and radiation--The rate of heat-transfer through the intra-clothing zone is proportional to the temperature-gradient between the skin and the ambient atmosphere, and inversely proportional to the resistance afforded by the insulation. The thermal gradient across the clothing is therefore directly proportional to the insulation for any given rate of heat-transfer. It may be considered to be 1°F for each one-quarter inch of effective thickness of clothing or still air for each three kg-cals/m^2/hr of heat-loss. This estimate applies only to dry insulation (undisturbed by air-movement) maintaining a value equivalent to still air. The actual heat-transfer from fiber to fiber through the layers of clothing is a complex combination of conduction and radiation, and no attempt is made here to analyze these complexities.

Convection--Two factors of air-movement increase the simple flow of heat. The first concerns convectional air-movement caused by sharp thermal gradients in the larger dead-air spaces. These are most important in the zone closest to the body where the slight air-movement conducts away the heated air and modifies the temperature-gradient at the source of heat. The second erodes the relatively stagnant layer of air-insulation on the exterior of the clothing, thus reducing the difference in temperature between the clothing-surface and the ambient air. The force of this outer moving air decreases the thickness of the clothing and air-spaces by compressing the layers more tightly, thus reducing the effective insulating thickness. If the structure of the clothing-fabric permits the penetration of this moving air through the interstices between the threads and fibers, there proceeds an effective exchange of ambient air with intra-clothing air.

This becomes increasingly effective as the temperature deviates either upward or downward from the neutral-comfort zone. The index of clothing-effectiveness in the latter cases of air-penetration is entirely dependent on the nature and air-proofness of the clothing-layers, especially the outer one. For the naked man the factor of air-erosion can increase normal conduction and radiation heat-losses by at least three and one-half times. This value for air-movement is felt only in the naked state and drops off in importance as the clothing-layers become increasingly thick.

Evaporation--Water-transfer in quantity and rate during evaporative cooling depends on the difference in vapor-pressure between the surface of the skin and the local atmosphere. It therefore is considerably modified by air-movement which, by the exchange of air, lowers the humidity (and vapor-pressure) close to the skin, and thus increases the rate of evaporation. The body exercises economy of its water-loss by keeping the skin relatively dry, unless conditions of heat-stress demand the full use of this mechanism. Under normal comfortable conditions the rate of water-loss is approximately that to be expected if only one-tenth of the body-surface was wet.

When there is slight air-movement the rate of evaporation is directly related to the difference in vapor-pressure between the skin and the atmosphere and may be taken as having a heat-equivalent of two kg-cals/m^2/hr per mm-of-mercury difference in pressure for an insulation-thickness equivalent to one-quarter inch of still air. The rate of evaporation under such conditions is inversely proportional to the thickness of the insulation.

When the relative humidity of the atmosphere is high, fibers of garments tend to come into moisture-equilibrium with the prevailing relative humidity. This means that under very humid conditions several ounces of water may be absorbed by clothing without the wearer being conscious of its presence. When the garments are heated by the temperature of the body, the relative humidity within the clothing is lowered and the fabrics release moisture for cooling by evaporation.

This, perhaps, more than any other factor causes so-called wet-cold to be more disagreeable than dry cold in the neighborhood of freezing-temperatures. At extremely low temperatures, the amount of absolute moisture available in the atmosphere is so slight that the fibers require a considerable period before they are able to regain their full moisture. In fact, below freezing-

Table 1--Typical calculations of formula $M = [Kc (T_s - T_a)/I] + [Ke (VP_s - VP_a)/I]$ for various stations for month of July

Climatic conditions	Calculations	Body wet, clothes dry	Body wet, clothes wet
		kg cals/m^2/hr	
Washington, D. C.			
Average wind-velocity, miles per hour. 5.2	Convective heat-loss per °F = 9 kg cals/m^2/hr		
Average maximum temperature, °F 86.4	Total loss by convection and radiation	74	86
Average vapor-pressure, mm of Hg 18.1	Evaporative heat-loss	105	535
Activity causing oppressive discomfort		179 (marching)	
Absolute limit of safe activity			621 (ditch-digging)
Sibsagar, Assam			
Average wind-velocity, miles per hour. 1.9	Convective heat-loss per °F = 5		
Average maximum temperature, °F 89.2	Total loss by convection and radiation	32	39
Average vapor-pressure, mm of Hg 24.8	Evaporative heat-loss	62	215
Activity causing oppressive discomfort		94 (slow walking)	
Absolute limit of safe activity			254 (running)
Lahore, India			
Average wind-velocity, miles per hour. 2.5	Convective heat-loss per °F = 6.5		
Average maximum temperature, °F 99.9	Total loss by convection and radiation	-15.8	-21.4
Average vapor-pressure, mm of Hg 21.8	Evaporative heat-loss	83	335
Activity causing oppressive discomfort		67 (sitting)	
Absolute limit of safe activity			314 (fast running)

conditions it is questionable whether the fibers are able at all to reach their normal water-content, or regain, as it is referred to by the textile trade. Experimentation in this field is so limited that the answers are not apparent.

When garments become wet, the insulation-effectiveness of the clothing is sharply decreased. As previously mentioned, some of this is due to such minor differences as the effect of clothing-fibers losing their structural strength. Other factors are increased heat-conduction of the water which replaces dead air, and the fact that the wetted fabrics cling more closely to the heated body-surface.

However, by far the most important reason for the reduction in thermal insulation is that the wet garment provides greater source for evaporation. Until the fibers and the air between them reach 100 per cent saturation, a moisture-gradient exists between the skin and the ambient atmosphere, which may be most conveniently expressed as a vapor-pressure gradient. If this gradient reaches its lowest limit outside the clothing, the vapor will pass through all layers until it is liberated into the outside atmosphere, or until it reaches a barrier which permits condensation. If the vapor-pressure gradient becomes broken, or reaches the dew-point within the clothing, condensation will take place.

By controlling ventilation and air-flow within heavy layers of garments, all sorts of local anomalies may be set up. Water in liquid form from either atmosphere or body, or both, may drench the narrow climate-zone; vaporized moisture may saturate it. It is not unusual to have a frost-line within a sleeping-bag when the temperature-gradient crosses 0°C within the clothing itself. Minute local storms may be caused by the movement of man's arm so that the amount of air within his sleeve rises and falls like the air in a bellows. All these variations and many more--too numerous to mention here--are significant in the study of environmental protection.

With full knowledge of the nature and rates of heat-loss through garments, it is possible to measure the insulation-value of garment-assemblies for any given environmental condition. Climatic maps have been drawn showing the insulation required for all types of weather; and from ones being drawn at present it will be possible to see how much more body-heat a man must create in damp cold than in dry if he is to keep his body in equilibrium.

For hot areas, where the amount of clothing varies less, this second form of description is more useful, because it makes possible a direct comparison of the strains imposed by the various climatic factors.

Table 1 gives examples of correlation between the climatic demand and the bodily activity. Two definitely hot, humid stations have been chosen and compared with Washington, D. C., under the same conditions. As a preliminary index, this serves to show how hard a man may work in the different regions for two states of bodily comfort: (a) Activity at which extreme discomfort is encountered without any danger experienced, that is, where the clothing is entirely dry and the skin surface covered with sweat--while somewhat artificial, this at least represents a reasonable average of oppressive discomfort; (b) the amount of activity which the man can maintain indefinitely without gaining bodily heat.

In order to simplify this index for rule-of-thumb use, three assumptions have been made: (1) The skin temperature is assumed to be 96° F; (2) conduction and radiation have been taken as a skin constant, although outside the jungle they may vary widely; (3) the insulation of the dry clothing alone will amount to 0.17 inch. The insulation of the wet clothing alone clinging to the body will amount to 0.1 inch. Resistances for clothing and air have been calculated for each wind-velocity. These have been added together and converted to kg cals/m^2/hr.

The figures on the Table are keys to the comfort and danger levels of the three regions. It will be seen that a man will not feel oppressively hot in Washington unless he is marching, while he can actually ditch-dig before he reaches a danger state. In Sibsagar, he will feel the oppression if he is walking slowly or be in danger if he runs, while in Lahore the oppressive heat will strike him if he is sitting down. He will, however, be able to run considerably faster than in Sibsagar due to the effect of the wind-velocity.

In actual fact, of course, a man may perform harder activities than those indicated, but only with danger since he will be adding to his bodily heat. The absolute limit represents then the boundary of the safety zone for the average unacclimatized white man under the conditions specified.

Maps, which are at present being laid out, will continue the study of this index throughout world-wide conditions, taking the radiation of Sun, percentage of cloudiness, the effect of wet-cold, and many other climatic variables into full account. The study of these relationships and of their action upon the body throughout the intra-clothing climate is making possible a better means for the Quartermaster to design its clothing for a world-wide army, and the results should provide some radical scientific improvements for post-war civilian clothing.

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CLIMATE AND BUSINESS

Eugene Van Cleef

Most of the persons in this audience are familiar with the fact that the United States Weather Bureau has made a number of climatological studies related to agricultural pursuits and that these investigations have had considerable practical value. Also, smaller organizations and some individuals here and there have engaged in climatological research on their own and these, too, yielded benefits to those engaged in agriculture. Then, too, there are those who have suggested correlations between climate and human endeavors other than agriculture. We readily recall WARD'S first edition of Climate [see 1 of "References" at end of paper], published 36 years ago, which aroused a lively interest in many quarters concerning man's reaction to climate. Witness the philosophy advanced by ELLSWORTH HUNTINGTON in his volume Civilization and climate [2] and in his other books and shorter papers. Climate makes the man [3] by CLARENCE MILLS records the physiological reactions of people to their climatic environment and offers some intriguing ideas involving the practical application of the author's observations. These are but a few of a long list of books and papers which might be cited as an expression of the desires of men to unearth specific relations between man's economy and the atmosphere which envelops him. It is not my purpose to trace this historical record in detail. However, as a basis for the suggestion which I shall offer later, I review a few individual investigations.

At the turn of the century, the cranberry growers of Wisconsin found themselves confronted by the problem of rescuing their business from the hazards of atmospheric uncertainties, more particularly frost-damage. They appealed to the United States Weather Bureau for relief by way of special frost-warnings. Weather Bureau officials reviewed the whole problem with the growers to learn just what they wished the Bureau to do and what hope the Bureau might hold out to them. Although the Weather Bureau was already doing its best with the knowledge then at hand, it undertook a program beginning in 1906 which involved essentially an investigation of the micro-climate of the Wisconsin cranberry-marsh region [4].

After several years of observations and correlations followed by an extension of the study of bog-climates to the bogs of Massachusetts, Weather Bureau men increased their forecast-accuracy notably and also aided the growers in improving their techniques, such as flooding for protection, subsequent draining, and avoidance of sun-scald of the fruit.

Some persons may prefer to classify this investigation under the heading of micro-meteorology rather than micro-climatology. This is not an important issue. The significance of the case lies in the approach to the problem. The investigation did not arise out of the enthusiasm of a climatologist or a meteorologist for learning certain facts concerning the behavior of the atmosphere in the cranberry-marsh locality just for the general satisfaction of increasing our sum total of knowledge, but rather arose out of the need for applying scientific techniques to the solution of an economic problem. I recapitulate the procedure. First, the grower recognized his problem; secondly, he cast about for a solution which might insure his own economic stability; thirdly, he appealed for assistance to a school of men not versed in the details of his general activity, but possessed with the skill to study the elements causing the trouble. There followed an investigation involving (1) the collection of climatological data, (2) a correlation of these data with the general atmospheric circulation of the region, and (3) a series of experimental forecasts which led to a satisfactory handling of the whole problem.

In the early 1900's A. W. DOUGLAS, high official of the Simmons Hardware Company of St. Louis, Missouri, found it possible to apply to his business current weather-forecasts for all parts of the Nation and also his own analyses of climatological data released by the Weather Bureau. He thought other lines of business should enjoy the benefits of his findings in so far as they could be applied. As Chairman of the Committee on Statistics and Standards of the Chamber of Commerce of the United States, he published several bulletins revealing his methods [5]. His ability to anticipate precipitation-deficiencies in certain seasons, excessive heat, or other departures from the normal enabled his organization to make important adjustments with reference to the flow of certain types of commodities and to orient their policy with respect to credits and collections. DOUGLAS' work was more or less of a hobby to him. No doubt, had he had the assistance of a well-trained climatologist he could have reaped even greater benefits than those which he did enjoy. I ask you to note again that the approach here was not by someone interested in climatological studies for their own sake, but rather by one who had problems to solve within his business and which he thought were affected by climate. The application of the science of climatology arose not from without but from within the business realm.

About 20 years ago the United States Department of Commerce issued a Bulletin on the subject of Weather and construction [6]. The purpose of this study was "the determination of average and extreme weather-conditions affecting building construction in nine large cities." The assumption of those who originated the investigation was that the favorable period for construction-work in regions with seasons of freezing weather or excessive rains or high winds or other so-called adverse condition need not be curtailed. If architects and contractors had proper data available they could adapt their building schedules accordingly, thereby lowering the peak-load of summer and spreading employment throughout the year. The publication was "part of a movement to supply scientific aids for builders who choose to challenge the seasons."

The authors of this report recognized certain limitations in the report itself and certain complexities in the whole problem. Experience has shown that in some instances the cost of building under adverse weather-conditions is higher than normal and that the quality of construction is poorer. The materials themselves often exposed to low temperatures or to alternate freezing and thawing or to excessive moisture at the time of erection yield inferior results. In spite of these aspects, the fundamental idea underlying the project was sound. It might have led to more effective results had the building industry itself played a greater part in the research and had there been a joint long-time program worked out.

Another illustration of the attempt to apply climatology to business is given here from my personal experience. Some years ago I became interested in the possible relationship between street-car passenger-traffic in Duluth, Minnesota, to daily and seasonal weather [7]. If a correlation could be made, then it seemed one might expect to be able to predict the probable patronage daily or seasonally with an accuracy limited only by the errors in the findings themselves and by the accuracy of the weather-forecasts. Without relating the method of procedure, I turn to the results.

I found a definite correlation. Forecasts of passenger-traffic were made within a maximum error of five per cent as long as the weather-forecasts proved accurate. The average error was 3.2 per cent. In absolute terms, the largest error in number of passengers predicted was 8,918 for a day on which 80,235 were carried, and the smallest was 33 on a day when 67,147 passengers were carried. These extremes are without reference to the quality of the weather-forecast.

The application of these results ran into a snag. The street-railway company was highly cooperative during the investigation and, while interested in the results, was unable to utilize them fully. The primary reason was the small size of their organization which provided for little or no flexibility. They had a negligible number of "trippers", that is, extra cars at any given time. They could not lay off or take on extra workers, but rather had to utilize full crews constantly, whether conditions on a given day warranted or not. They did believe that in larger cities, beginning perhaps at the 500,000 level, the application could have great practical value if similar correlations were true. Duluth's population at the time was just under 80,000.

The fact that my investigation could not be utilized in toto in Duluth did not necessarily vitiate its worthwhileness. Similar surveys in other cities, particularly larger ones, were in order, but unfortunately it was not practicable for me alone to undertake this expansion. Again such surveys in other centers in regions of radically different climates might reveal results far less encouraging. On the other hand, they might yield principles of far-reaching value.

My street-car traffic research gave rise to an incidental observation which emphasized the need for just such investigations as I have been discussing. The traffic observation showed, among other things, that "moderate to strong winds, usually of strength 4 or above (Beaufort scale)", reduced the number of passengers. However, the largest department store had noticed that, whereas their receipts fell off on the first two days of a typical Duluth three-day strong northeaster, their receipts began an upward climb toward normalcy on the third day. Why this upturn?

Perhaps enough cases have been cited, in the time available, to suggest one avenue along which applied climatological investigations may well be directed. It is my belief the problem should originate within the confines of a particular field of business. We should find out from those engaged in a given activity what problems they have which seem to them to be affected by climatic or weather-conditions and then to set the stage for our research. Note, I emphasize a field of business rather than one firm and I would add that the investigation must take cognizance of different climatic settings. The climatologist would thus begin with the support of an entire industry which would make available its experiences and its judgments. This investigator would bring to bear his ability to recognize variables which might enter the problem and, of course, his expertness in planning for the collection of the proper data under satisfactory conditions and their subsequent synthesis and analysis.

A little reflection upon this situation by any one of us must quickly bring home the fact that such procedure as I have indicated involves a Herculean, if not impossible, task for an individual working alone. Such studies in many instances are of the same order as agricultural climatological studies. And just as the latter have been made largely with the support of the National Government involving many workers, so these analyses of business as affected by climate and weather demand a similar working program. These studies could be undertaken jointly by the United States Weather Bureau and the United States Department of Commerce. That this joint action would yield far-reaching results for the benefit of the business world and hence the Nation seems to me a reasonable expectation.

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DISCUSSION

W. A. MATTICE (U. S. Weather Bureau, Washington, D. C.)--Dr. VAN CLEEF'S paper is quite timely and it highlights a problem that the Weather Bureau has been studying in such time as it can spare from the war demands. A preliminary survey was made of correspondence in the Climate and Crop Weather Division covering a period of a year. This survey disclosed an assortment of unusual requests and also revealed that quite a number of requests were received from persons who had been previously acquainted with the Weather Bureau service.

A total of 3,886 inquiries were reviewed, broken down into 16 major groups. Of these, requests from the general public were the larger, comprising about 22 per cent of the total. Requests from lawyers and litigants totalled 19 per cent, governmental agencies 14 per cent, and transportation-companies seven per cent. Manufacturing, merchandizing, and construction engineering only accounted for 12 per cent of the total.

The problem as outlined by Dr. VAN CLEEF is not one of a general coverage of the entire economy of the Nation, but rather the determination of a definite course of action whereby a specific industry at a time is made acquainted with the available data and problems are outlined to be solved either through use of existing information or through a coordinated program that will collect and analyze data and recommend solutions. This will involve close cooperation between the governmental agencies and the representatives of the industry so that representatives of each will be contributing their best abilities to the problem.

This approach to the situation would seem productive of significant results if logically and persistently followed. It is not beyond the realm of possibility that, given a return to peace-time conditions, action can be taken to secure such successful cooperation.

SOME USES AND DEFICIENCIES OF CLIMATOLOGICAL DATA

Karl F. Keeler

(1) Climatological data are basic building materials of hydrology. To make these materials more accessible to the profession they should be presented differently. But first they should be gathered together and supplemented where necessary.

(2) The wide use of topographic and geologic data by engineers is largely due to the form in which these complex data are presented. The level-notes, plain-table sheets, well-logs, and the rock- and soil-samples have not been left in the hands of the private or public agencies who gathered them. They have been collected together, checked and supplemented where necessary, and then integrated into topographic maps or geologic maps, or significant profiles or cross-sections. If climatological data were similarly synthesized for presentation to the profession, their use would likely also broaden greatly. In just what form climatological data should be presented and what standards should govern their collection only the experience of many men in related fields and in many localities may show. Possibly the Section of Meteorology of the American Geophysical Union may be of service in this direction.

(3) There are two objectives in showing here some manipulations of climatological data: First, to illustrate the gathering together of a mass of such data and its synthesis into usable form; second, to illustrate the usefulness of such data in several types of hydrologic problems.

(4) The use of climatological data in evaluating water-resources of a region is not new. Because of the great accumulation of such data in recent years, advancement is taking place in the methods of its use and in the reliability of the results attained. Some of the features of these advanced methods are taken from statistical procedures and some from common practice in the related fields of meteorology and hydrology. Because several of the equations presented here are new, some little explanation is presented which may not seem germane to the main theme.

(5) Some of these new equations [for example, equations (1) and (4)] are most likely applicable, without change, to any region while others, especially those in paragraph (22), may or may not be applicable in other regions without some change of coefficients and probably also some change of form. Something more is said of this point later on.

(6) The illustrations used in this paper are from the subdivision of the Rio Grande Watershed lying in the United States and Mexico between Fort Quitman, which is 80 miles downstream from El Paso (Texas) and Upper Presidio. Tributary to this 205-mile stretch of river there are 3,010 square miles, 1,621 in the United States and 1,389 in Mexico.

(7) All available rainfall-records from every station in or adjacent to the Rio Grande Basin below El Paso have been assembled and indexed alphabetically, chronologically and positionally along the main river and its principal tributaries [see 1 of "References" at end of paper]. The above records include those collected by: (a) United States Signal Corps at Army posts as early as 1871; (b) Galveston, Harrisburg, and San Antonio Railway Company, San Antonio to El Paso; (c) United States Soil Conservation Service; (d) United States Weather Bureau; (e) Mexican Meteorological Service; (f) local ranchers; and (g) International Boundary Commission. Such multifacet indexing has contributed greatly to the understanding of this otherwise complex mass of records and to the ease with which these records may be used.

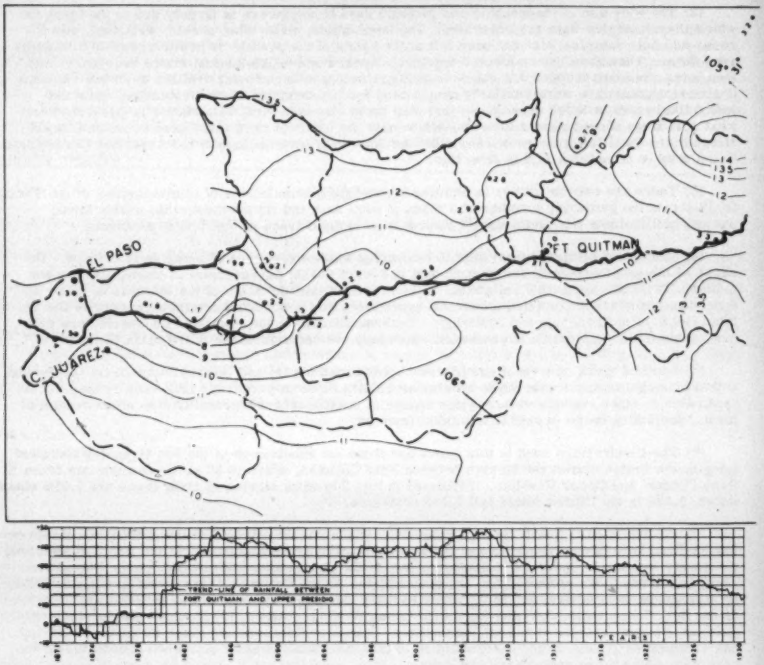
(8) The following definitions apply to the ensuing equations (1) to (4) and to their discussion:

r = inches depth of rainfall at a station for a particular month
r′ = average inches depth of rainfall at a certain station for a given month and over a certain base-period of several years
R = same as r except the R applies to an area of watershed instead of to a station
R′ = same as r′ except the R′ applies to an area of watershed
d = distance from station x to different stations
a = the angle controlled by a given station (considered as one-half the open angle on each side of the given station, station x being at the apex of the angles)
n = (See e in paragraph 10)

Subscripts 1, 2, 3, etc., indicate different stations simultaneously. Subscript x indicates the station for which rainfall is to be computed.

(9) From a study of a large number of rainfall-records it was found that within reasonable limits of general accuracy the rainfall at station x for any particular month (r_x) may be computed by equation (1).

$$\left[\frac{\frac{r_1}{r_1'} + \frac{r_2}{r_2'} + \frac{r_3}{r_3'} \text{ etc., to n terms}}{n}\right] r_x' = r_x \qquad (1)$$



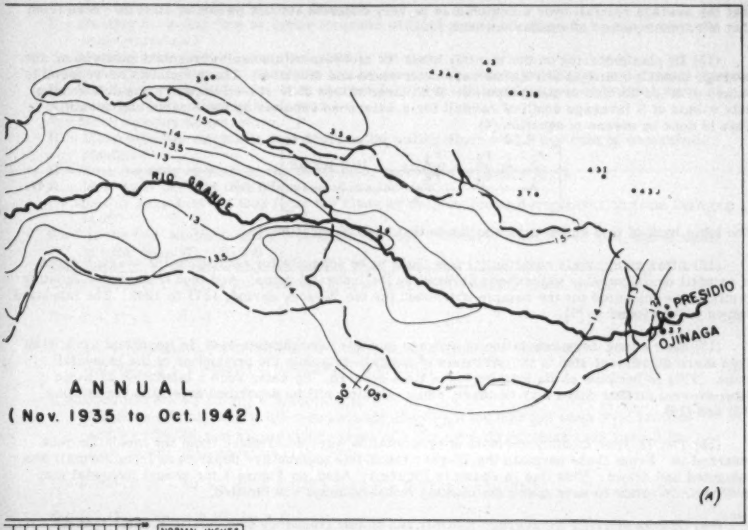
The years in the base-period must be the identical years for all stations for any one application of the equation.

(10) The use of this equation requires judgment, but a satisfactory degree of general accuracy is maintained if the following points are observed:

(a) The location of stations 1, 2, 3, etc., should be as close as possible to station x.
(b) Stations 1, 2, 3, etc., should be dispersed at as near equal angles about x as possible.
(c) Unless other limitations require it, two stations need not be used in the above equation if they lie at about the same azimuth from x, but only the closer of the two should be used.
(d) The number of years in the base-period for values r_1', r_2', r_3', etc., should be five years or more, if possible.
(e) The number of terms in the equation may vary from two to five, preferably three or more.

(11) In the various studies leading up to the adoption of equation (1), the equations (2) and (3) were tried at considerable length.

$$\left[\frac{\left(\frac{r_1}{r_1'}\frac{a_1}{\sqrt{d_1}} + \frac{r_2}{r_2'}\frac{a_2}{\sqrt{d_2}} + \frac{r_3}{r_3'}\frac{a_3}{\sqrt{d_3}} + \text{.... to n terms}\right)}{\left(\frac{a_1}{\sqrt{d_1}} + \frac{a_2}{\sqrt{d_2}} + \frac{a_3}{\sqrt{d_3}} + \text{.... to n terms}\right)}\right] r_x' = r_x \qquad (2)$$



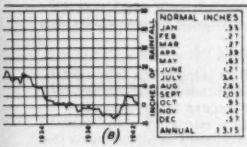


Fig. 1--(A) Seven-year average rainfall; (B) 72-year trend of average rainfall between Fort Quitman and Upper Presidio, 1871 - 1942

$$\left[\frac{\frac{r_1}{r_1'}\frac{a_1}{d_1} + \frac{r_2}{r_2'}\frac{a_2}{d_2} + \frac{r_3}{r_3'}\frac{a_3}{d_3} + \text{.... to n terms}}{\frac{a_1}{d_1} + \frac{a_2}{d_2} + \frac{a_3}{d_3} + \text{.... to n terms}}\right] r_x' = r_x \qquad (3).$$

Equations (2) and (3) were finally dropped because of the greater simplicity of equation (1) for which the results were found to be generally as satisfactory.

(12) By use of equations (1), (2), and (3)--mostly equation (1)--the monthly rainfall was computed for the months of missing record within the seven-year period, November, 1935, through October, 1942, for each of the many rainfall-stations used in preparing the isohyetal maps. One map was made for each month of the year and another for the annual. These 13 maps each covered the above-mentioned seven-year period.

(13) The transparent work-sheets used in drafting these maps were laid over a topographic map of the region in order to use the topography as a secondary guide in sketching in the isohyets. This resulted in the isohyets and the contour-lines often paralleling each other.

(14) Detailed monthly and annual isohyetal maps are always very instructive for the region represented. They are an important step in the synthesis of precipitation-data. But for such maps to be of greatest service they must be based upon an adequate accumulation of precipitation-records for the period which they represent and the period covered should probably be not less than seven years. Furthermore, such period should be shown on the map, for it has been found frequently

that the average rainfall over a region may be very different for one period of 10 to 20 years from that of another period of similar duration [10].

(15) By planimetering on the monthly maps the isohyets within each watershed subdivision, the average monthly amounts of rainfall were determined and tabulated. These amounts correspond to values of R′ as defined in paragraph (8). With these values of R′ it then becomes possible to compute values of R (average depth of rainfall for a watershed subdivision for a particular month). This is done by means of equation (4).

$$\left[\frac{\frac{r_1}{r_1'} + \frac{r_2}{r_2'} + \frac{r_3}{r_3'} + \ldots, \text{ to n terms}}{n}\right] R' = R \qquad (4)$$

The logic back of this equation is similar to that back of equation (1).

(16) After many trials equation (4) was found to be adequate for computing the average depth of rainfall on the various watersheds covered by the isohyetal maps. And thus the average monthly rainfall was computed for the sample watershed for the 72-year period, 1871 to 1942. The tabulated values will be found in [5].

(17) Such a long-term tabulation of average monthly precipitation over an important area is an even more significant step in the synthesis of rainfall-data than the production of the isohyetal maps. This is because of the long period of time covered. By using such a tabulation as basic data, several further steps may be taken, some of which will be described briefly in paragraphs (18) and (19).

(18) The 72-year monthly normals of precipitation were determined from the tabulation just referred to. From these normals the 72-year trend-line (cumulative departures from normal) was computed and drawn. This line is shown in Figure 1. Also, on Figure 1 the annual isohyetal map is shown. In order to save space the monthly isohyetal maps are omitted.

(19) Graphs showing the average monthly and annual frequency of rainfalls greater than or less than the median may easily be prepared from such a long-term tabulation as that mentioned in paragraph (16). Such a set of graphs will be found in [11].

(20) The gathering together of a mass of climatological data, and its integration into usable forms, has now been illustrated. This completes the first objective mentioned in paragraph (3). Before the second objective can be undertaken it is necessary to have access to several other types of data. These are temperatures, river-flows, irrigated acreages, and wind-velocities. These data, except the wind-velocities, likewise relate to the same watershed subdivision on the Rio Grande. The tabulated mean monthly temperatures above 40°F will be found in [2]; the monthly river-flow records will be found in [3]; the annually irrigated acreages will be found in [4]; the departures from monthly wind-velocities for an adjoining watershed-area will be found in [2]. From a knowledge of the time of river-water travel across this watershed, that is, from Fort Quitman to Upper Presidio, and by using daily flow-records, the records of monthly flow were adjusted so that the monthly amounts leaving the watershed at Upper Presidio correspond in time with the amounts that entered the watershed at Fort Quitman during each calendar month.

(21) The second objective may now be undertaken, that is, illustrating the usefulness of climatological data in a few types of hydrologic problems. The aforementioned data on rainfall, temperature, acreage irrigated, and river-flow entering and leaving the watershed were taken for the basic period 1927 to 1942 during which these records were most complete. From these data for this period and for this watershed and river-channel the equations (9) to (16) were developed. The method of least squares and other methods of balancing were used in their derivation so that cumulative errors were avoided. They were based upon experience or data for the period 1927 through 1942 (16 years), but because of the very wide range experienced during this time in the different variables these equations are presumed to be applicable to many previous years. For example, the year 1934 had a very small rainfall and very high temperatures, the year 1941 had very large rainfalls, and the year 1942 was one of very large river-flows originating upstream from this watershed.

(22) The definition of terms, the equations, the coefficients, and constants are as follows:

F = Monthly acre-feet flow at Fort Quitman
U = Monthly acre-feet flow at Upper Presidio with the month so timed as to encompass the same water as F
Y = Monthly acre-feet of watershed-yield to the river
L = Monthly acre-feet of river-water lost by evaporation, bank-vegetation, and channel-seepage
B = Monthly acre-feet of river-bank storage (-) and river-bank return (+) in flood-time
A = Total acreage irrigated each year
T = Mean monthly temperature, °F
R′ = Mean monthly rainfall in feet depth on the valley-floor = 92.9 per cent of watershed-rainfall
R = Mean monthly rainfall on the watershed, expressed in inches depth
R = Same as R but only that in excess of six inches
I = Monthly acre-feet net loss from the river by evaporation and transpiration from farming land
I = 0 in the four winter months, November through February, when $A > 15{,}000$, and in other months when $(F + Y) = 0$
Subscripts 0, 1, 2, etc. = Current month, first preceding month, etc., respectively
Coefficients c, C, k, and the constant K have the monthly values shown in Table A.

$$U = F + Y - L + B - I \quad (8)$$

$$Y = K + k\,(0.00917R_0^2 + 0.03166R_0 + 0.01667R_1 + 0.0108R_2 + 0.0083R_3 + 0.0067R_4 + 0.0042R_5 + 0.0033R_6 + 0.0017R_7) \quad (9)$$

$$L = 5{,}000\,[C\,(T - 40°) - R'] + 2{,}100 + 0.12\,F \quad (10)$$

[Equation (10) applies in all cases except when $F_0 > 110{,}000$ and when $F_1 < 110{,}000$ and $F_2 < 30{,}000$ and all previous values of F for over three years have been less than 70,000, then equation (11) applies.]

$$L = 5{,}000\,[C\,(T - 40°) - R'] + 2{,}100 + 0.12\,F + 0.77\,(F - 110{,}000) \quad (11)$$

$$B = 0.1\,(F_1 - F_0) + 0.05\,(F_2 - F_1) \quad (12)$$

(This equation is used only when F_0, F_1, or F_2 is 70,000 or more.)

$$I = A[c\,(T - 40°) - R'] \text{ in the summer months when } A > 15{,}000 \text{ and } F > 0 \quad (13)$$

$$I = [A + 1/3\,(17{,}500 - A)]\,[c\,(T - 40°) - R'] \text{ in summer months when } A < 15{,}000 \text{ and } F > 0 \quad (14)$$

$$I = [1/3\,(17{,}500 - A)]\,[c\,(T - 40°) - R'] \text{ when } F = 0 \text{ and } Y > 0 \text{ and for those winter months when } A < 15{,}000 \quad (15)$$

$$I = [1/3\,(17{,}500 - A)]\,[c\,(T - 40°) - R'] + [1/4\,(17{,}500 - A)]\,[c_1\,(T_1 - 40°) - R_1'] \text{ when } F_1 + Y_1 = 0 \quad (16)$$

When (L + I) computed by the above equations is greater than (F + Y - U), then the final values of L and I are adjusted by judgment to make (L + I) = (F + Y - U).

Table A

Month	c	C	K	k	Month	c	C	K	k
Jan.	.....	.010	-2,000	62,620	July	.0199	.0250	- 4,000	196,967
Feb.	.....	.010	0	45,226	Aug.	.0172	.0167	- 4,000	207,508
Mar.	.0084	.010	0	83,018	Sep.	.0104	.0125	- 5,000	143,697
Apr.	.0167	.010	1,500	69,948	Oct.	.0050	.010	-20,000	259,769
May	.0129	.0167	3,000	115,780	Nov.	.....	.010	0	43,752
June	.0118	.0208	3,000	143,781	Dec.	.....	.010	0	28,893

(23) By means of equations (8) to (16) the Rio Grande flow at Upper Presidio can be calculated from the known flow at Fort Quitman, or by successive approximations, the flow at Fort Quitman can be calculated from the known flow at Upper Presidio. The reliability of this method of calculating the flow at Upper Presidio is indicated by Figure 2. The coefficients of correlation between measured and computed values are also shown thereon. From these equations, of course, the values of Y, L, I, and B can all be computed. Tabulations of the computed values for many years past, as well as values of F and U, will be found in [3].

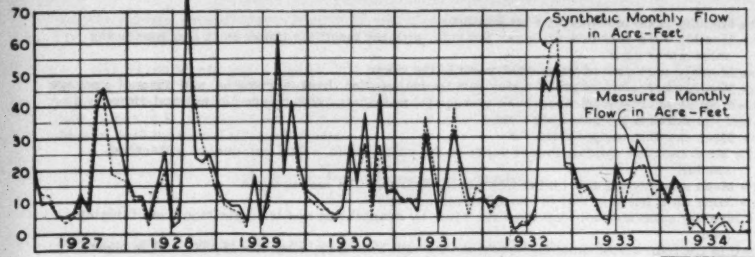


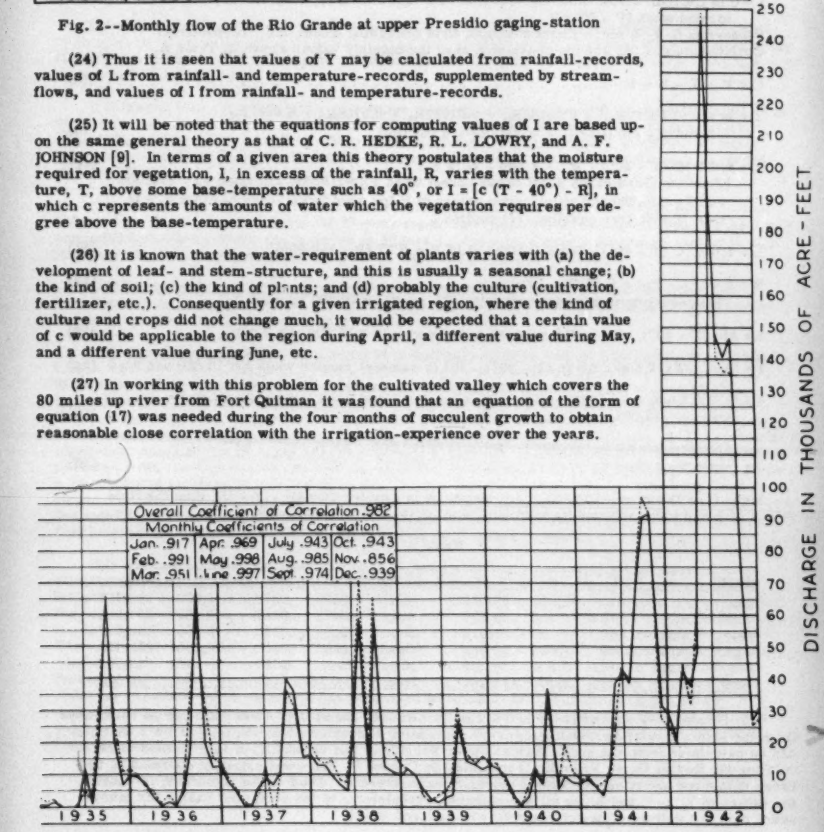
Fig. 2--Monthly flow of the Rio Grande at upper Presidio gaging-station

(24) Thus it is seen that values of Y may be calculated from rainfall-records, values of L from rainfall- and temperature-records, supplemented by stream-flows, and values of I from rainfall- and temperature-records.

(25) It will be noted that the equations for computing values of I are based upon the same general theory as that of C. R. HEDKE, R. L. LOWRY, and A. F. JOHNSON [9]. In terms of a given area this theory postulates that the moisture required for vegetation, I, in excess of the rainfall, R, varies with the temperature, T, above some base-temperature such as 40°, or $I = [c\ (T - 40°) - R]$, in which c represents the amounts of water which the vegetation requires per degree above the base-temperature.

(26) It is known that the water-requirement of plants varies with (a) the development of leaf- and stem-structure, and this is usually a seasonal change; (b) the kind of soil; (c) the kind of plants; and (d) probably the culture (cultivation, fertilizer, etc.). Consequently for a given irrigated region, where the kind of culture and crops did not change much, it would be expected that a certain value of c would be applicable to the region during April, a different value during May, and a different value during June, etc.

(27) In working with this problem for the cultivated valley which covers the 80 miles up river from Fort Quitman it was found that an equation of the form of equation (17) was needed during the four months of succulent growth to obtain reasonable close correlation with the irrigation-experience over the years.



$$I = [c\,(T - 40^\circ) - R' + k\,W] \qquad (17)$$

Here W represents the departure from normal wind-velocity in miles per hour and k is a monthly coefficient. During the other eight months the kW-term was not needed. It is presumed that the reason for not needing the kW-term in the equations for I, from Fort Quitman to Upper Presidio, is because the irrigated land in this stretch lies in a narrow valley between mountains which minimize the wind-effect.

(28) In a like manner the equation from paragraph (22) for computing the normal values of L is seen to consist of three parts. Each of these parts is presumed to reflect some characteristic of this particular stretch of river-channel. So if this equation, or, in fact, any of the equations from paragraph (22) are to be used elsewhere, judgment should be used in modifying their terms to conform to the particular conditions of the new location.

(29) The use of climatological data to gain an approximate understanding of the monthly rates of dissipation of water from upland and from valley-floor will next be illustrated. By designating valley-floor area as the relatively flat part of the area, between the hills and mountains bordering the Rio Grande between Fort Quitman and Upper Presidio, it was determined from topographic maps and aerial photographs that the valley-floor area was 50,100 acres. Then since the total area of the watershed between the two river gaging-stations is 3,010 square miles (1,926,400 acres) it is seen that there are 1,876,300 acres of upland.

(30) In the discussion of this subject the following definitions are used:

D = Acre-feet of water per month dissipated into the air by evaporation and transpiration from the entire watershed
Dv = That part of D dissipated on the valley-floor
Du = That part of D dissipated on the upland
R = Acre-feet per month of rainfall on the entire watershed
Rv = Same on the valley-floor = (50,100) (0.929) (0.08333) r = 3,878.42 r
Ru = Same on upland = (1,876,300) (1.0019) (0.08333) r = 156,649.15 r
$Ru' = 0.38Ru_0 + 0.2Ru_1 + 0.13Ru_2 + 0.1Ru_3 + 0.08Ru_4 + 0.05Ru_5 + 0.04Ru_6 + 0.02Ru_7$
r = Average monthly depth of rainfall on the entire watershed in inches
$\dot{r}$ = That part of r (if any) in excess of 6 inches
- above a symbol = average value
T, F, U, I, L, B, c, C, k, K, and subscripts 0, 1, 2, etc., are defined as in paragraph (22)
Y is defined here as = Acre-feet per month reaching the river from the upland rainfall

(31) There are three assumptions, all of which appear to be reasonable, which it seems necessary to make in arriving at the conclusions that follow. These assumptions will be found in paragraphs (32), (34), and (37).

(32) Assume that the only underground leakage of consequence into or out from the watershed is that passing underground in a direction downstream at Fort Quitman and Upper Presidio, and that these amounts at each station are approximately equal to each other month by month.

(33) From this assumption it follows that the water represented by L, Rv, and I is subsequently dissipated into the air on the valley-floor.

(34) The contributions to Dv from L, Rv, and I are known not to be complete within any given month. These contributions are assumed to be spread over three months as in equation (18)

$$Dv = 0.5\,(L + Rv + I)_0 + 0.3\,(L + Rv + I)_1 + 0.2\,(L + Rv + I)_2 \qquad (18)$$

Table 1, herewith, shows monthly values of Dv computed in accordance with equation (18), and in which values of Rv were computed from the table of monthly rainfall mentioned in paragraph (16), and in accordance with the above definitions of Rv. Tabulated values of I and L were taken from [6] and [7]. It is thus seen that Dv depends upon certain coefficients and areas as well as upon river-flow at Fort Quitman and finally upon mean monthly temperature and rainfall depth on the watershed.

(35) From the assumption of paragraph (32) and the definitions above, it follows that the water falling on the upland as Ru subsequently leaves the upland either as Y or as Du. Over a long period of years we may therefore write

$$\overline{(Ru - Y)} = \overline{Du} \qquad (19)$$

(36) From measurements, correlations, and deductions it was found [see paragraph (22)] that

$$Y = K + k\,(0.00917r^2 + 0.03166r_0 + 0.01667r_1 + 0.0108r_2 + 0.0083r_3 + 0.0067r_4 + 0.0042r_5 + 0.0033r_6 + 0.0017r_7) \qquad (20)$$

This equation shows the approximate average pattern of distribution of that portion of the previous rainfall which reaches the river each month from the upland.

Table 1--Average monthly dissipation on the valley-floor
(Dv expressed in thousands of acre-feet)

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
1889	6.0	5.0	5.9	9.6	15.5	20.8	23.4	18.9	17.0	10.5	7.0	3.1	142.7
1890	3.7	3.9	5.0	12.1	28.9	37.7	34.8	27.7	19.6	11.9	7.2	6.5	199.0
1891	6.3	6.2	10.0	18.6	41.4	49.6	40.3	25.5	15.0	13.3	8.9	7.1	242.2
1892	6.1	6.5	7.0	14.8	31.5	31.4	28.0	19.1	12.8	6.3	5.1	4.8	173.4
1893	4.5	4.2	4.1	6.5	22.7	19.1	24.2	22.5	19.3	11.4	6.0	4.4	148.9
1894	4.2	3.9	4.3	7.2	11.9	15.3	19.9	20.8	17.5	11.8	6.9	5.3	129.0
1895	5.6	5.5	6.3	10.9	28.6	32.1	35.9	28.4	21.0	14.6	10.7	7.7	207.3
1896	6.6	5.1	4.3	5.8	9.6	14.4	24.5	21.2	18.9	13.9	8.9	5.5	138.7
1897	4.5	4.3	4.0	10.2	27.3	46.2	44.7	35.1	23.8	17.9	11.5	8.6	238.1
1898	6.6	6.6	6.5	12.7	18.6	21.7	29.4	25.8	18.6	9.0	4.8	4.8	165.1
1899	4.4	4.2	4.3	7.3	8.2	10.9	20.7	18.4	15.7	8.4	6.7	5.0	114.2
1900	5.0	4.8	5.3	4.9	12.2	21.7	34.0	37.7	36.6	29.1	16.7	7.8	215.8
1901	3.9	4.4	4.8	5.6	16.3	16.9	20.1	17.2	12.5	15.5	9.3	5.8	132.3
1902	3.3	3.3	3.3	4.0	5.4	9.9	23.3	40.2	38.5	30.1	16.1	8.9	186.3
1903	6.6	6.0	7.6	12.6	35.6	133.9	90.6	68.2	30.3	19.3	10.1	3.5	424.3
1904	2.6	2.5	2.6	3.2	4.8	8.9	20.8	29.1	38.3	44.3	10.5	13.9	189.5
1905	7.4	12.6	26.6	33.7	58.2	80.5	47.7	40.1	17.6	19.5	14.8	13.0	371.7
1906	8.3	6.5	3.6	19.2	36.8	26.9	33.5	30.8	25.9	19.7	14.3	13.2	238.7
1907	13.7	9.5	8.8	17.3	35.3	47.2	44.7	38.2	22.7	19.5	8.5	5.2	270.6
1908	2.2	2.7	5.5	13.3	9.6	8.0	29.8	32.4	20.6	10.2	4.7	6.5	145.5
1909	6.1	6.1	6.7	12.6	22.9	24.3	22.1	21.7	20.1	12.3	8.8	6.9	170.6
1910	9.8	6.6	13.7	17.4	21.2	16.8	20.0	16.5	11.1	5.3	2.8	2.5	143.7
1911	3.8	6.9	13.1	11.4	19.6	35.9	62.0	26.0	28.9	30.6	21.0	16.8	276.0
1912	4.9	4.6	6.3	14.5	46.4	39.4	23.4	8.4	7.2	6.5	10.1	8.2	179.9
1913	7.7	9.1	6.4	12.0	12.5	16.8	16.1	28.1	28.7	27.0	16.9	10.7	192.0
1914	7.7	7.8	9.6	12.0	24.3	33.7	40.9	34.7	22.7	15.0	12.3	14.6	235.5
1915	10.9	8.8	7.7	9.4	12.8	16.9	24.9	25.2	25.1	14.8	8.4	4.5	169.4
1916	4.5	4.8	6.2	8.4	11.6	15.6	19.4	22.1	17.2	14.2	8.0	7.3	139.3
1917	6.8	7.5	7.5	8.6	10.3	13.2	22.2	28.8	25.3	17.7	10.9	8.5	167.3
1918	7.2	6.3	6.8	8.0	10.7	13.5	19.5	21.9	16.1	12.1	10.3	8.4	140.8
1919	6.0	4.5	6.7	10.0	13.6	16.1	23.1	22.7	26.4	22.7	16.6	9.6	178.0
1920	10.8	10.3	12.1	10.4	12.4	16.7	21.5	27.3	22.0	17.7	10.8	7.5	179.7
1921	5.2	5.1	7.0	8.8	12.4	17.3	25.6	26.3	23.8	16.8	13.5	9.7	171.3
1922	6.5	6.1	6.9	11.0	13.8	16.2	21.5	22.8	19.9	15.2	10.2	7.3	157.4
1923	6.0	6.9	7.5	9.7	11.8	15.5	22.5	28.6	23.8	17.9	10.5	8.4	169.1
1924	6.2	7.0	7.6	10.6	14.0	16.3	27.4	25.9	22.7	14.2	8.4	5.9	166.2
1925	4.4	4.7	5.8	9.1	13.2	16.0	21.4	26.2	24.4	17.7	9.7	5.9	158.5
1926	5.0	4.3	6.4	10.5	14.3	17.0	27.3	25.5	23.9	16.4	10.6	8.8	170.0
1927	7.4	7.5	6.9	8.8	10.9	13.6	24.4	28.9	27.1	10.6	1.1	1.1	148.3
1928	2.8	4.2	4.3	8.2	9.3	12.8	24.2	32.0	34.2	26.1	13.3	4.3	175.7
1929	1.4	2.0	3.5	6.6	13.9	15.3	21.4	20.7	18.6	17.5	7.8	4.8	133.5
1930	1.4	1.9	4.6	8.6	13.9	13.4	24.8	18.4	15.8	3.3	4.2	4.2	114.5
1931	7.9	7.7	9.2	20.7	19.1	23.7	24.2	30.3	21.7	10.5	7.4	8.3	190.7
1932	5.9	7.4	6.7	9.0	12.3	15.8	22.3	28.1	38.4	25.9	14.4	6.3	192.5
1933	3.4	4.1	3.7	8.1	10.1	19.4	18.0	23.4	13.2	11.8	3.3	3.5	122.0
1934	1.5	4.0	4.1	8.0	12.4	15.7	17.0	17.8	13.9	9.4	7.5	6.6	117.9
1935	6.3	5.8	4.8	4.5	5.9	9.6	14.3	29.6	25.5	20.7	12.3	9.4	148.7
1936	6.6	4.6	5.9	7.3	14.3	15.8	22.1	20.6	20.4	17.9	14.4	9.8	159.7
1937	6.1	4.9	5.2	7.2	13.4	16.0	16.4	18.9	18.3	13.0	9.8	11.4	140.6
1938	10.3	8.8	10.0	11.8	15.0	26.3	36.2	32.6	30.4	21.3	16.3	11.2	229.8
1939	8.9	6.1	4.8	8.2	11.8	16.1	22.3	26.0	22.7	15.8	13.1	9.0	164.8
1940	7.8	5.0	5.4	5.4	11.9	17.9	24.2	26.2	16.6	18.2	13.1	10.6	162.3
1941	7.9	6.4	8.6	13.6	11.7	19.3	23.5	32.7	43.0	26.5	12.1	3.1	208.4
1942	2.6	8.1	6.4	22.8	38.0	39.7	27.6	27.5	18.0	11.6	5.5	5.2	213.0
Total	319.2	313.6	367.9	582.3	980.3	1,300.7	1,493.0	1,449.9	1,209.3	891.4	551.9	400.9	9,860.4
Normal	5.9	5.8	6.8	10.8	18.2	24.1	27.7	26.8	22.4	16.5	10.2	7.4	182.6

(37) From this background the assumption is made that

$$Ru' = (Y + Du) \qquad (21)$$

This assumption implies the approximate average pattern of distribution of that portion of the rainfall which is dissipated into the air each month from the upland.

(38) Monthly values of Ru', expressed in thousands of acre-feet, were calculated in accordance with the foregoing which is also according to equation (22).

Table 2--Average monthly dissipation on the uplands
(Du expressed in thousands of acre-feet)

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
1889	127.4	93.6	72.9	56.3	34.1	78.5	214.4	146.2	279.3	194.9	146.9	103.7	1,548.2
1890	96.6	58.7	35.9	47.4	30.5	120.3	244.7	331.8	331.4	241.9	190.9	177.7	1,907.8
1891	132.8	84.3	55.7	25.7	60.5	57.8	64.6	96.0	145.6	95.9	66.1	83.3	968.3
1892	94.7	75.1	53.9	43.8	21.7	17.9	131.9	182.9	145.7	125.9	123.0	133.2	1,149.7
1893	89.2	71.5	59.3	34.7	210.5	115.0	288.4	415.4	374.8	237.1	189.1	166.6	2,251.6
1894	120.0	82.6	48.5	40.1	37.5	45.6	180.7	280.0	282.8	212.8	154.2	142.5	1,627.3
1895	129.2	97.2	55.7	32.9	178.7	127.2	376.0	425.4	366.1	290.5	273.6	207.4	2,559.9
1896	183.7	130.3	70.1	41.9	26.9	75.1	379.3	269.9	324.5	339.1	240.6	175.9	2,257.3
1897	149.2	99.1	59.3	51.0	72.8	155.0	397.8	470.6	452.9	323.0	244.2	185.1	2,660.0
1898	136.5	86.3	61.1	78.1	41.1	120.3	239.6	296.7	239.4	169.0	126.7	162.8	1,757.6
1899	102.0	64.2	39.6	92.6	44.6	94.2	360.7	246.5	244.6	180.4	174.4	140.7	1,784.5
1900	122.0	93.6	88.0	56.4	87.0	170.6	318.7	293.3	369.6	311.6	227.7	164.7	2,303.2
1901	132.9	106.4	68.2	63.7	41.1	50.8	175.6	147.9	194.2	264.7	200.1	137.0	1,582.6
1902	120.1	77.1	44.9	29.3	19.9	64.7	389.4	390.3	378.3	261.4	240.6	198.0	2,214.0
1903	176.5	137.6	77.2	61.9	64.0	224.5	199.2	224.7	275.8	183.7	126.7	96.3	1,848.0
1904	71.0	38.6	21.6	7.5	11.1	111.6	206.0	229.8	444.2	386.1	268.1	240.6	2,036.2
1905	189.1	163.3	161.7	141.5	78.2	208.8	389.4	273.3	305.3	250.0	277.3	238.8	2,676.7
1906	187.4	148.6	89.8	89.0	102.9	75.1	310.3	452.2	331.4	258.1	269.9	242.5	2,557.2
1907	167.1	113.7	73.7	41.9	27.0	49.1	118.4	248.2	230.7	326.2	218.5	153.6	1,768.2
1908	111.1	80.7	84.5	107.1	51.7	43.8	352.3	376.9	270.6	191.8	146.9	109.2	1,926.6
1909	78.3	47.7	16.2	2.2	1.2	49.1	239.6	169.6	129.9	99.6	86.3	96.3	1,013.6
1910	67.4	40.4	27.0	20.3	37.5	57.8	106.7	116.0	81.4	63.9	44.0	42.5	704.9
1911	47.0	93.6	86.2	58.2	79.9	212.3	285.0	234.8	269.0	175.6	141.3	144.3	1,827.2
1912	91.0	53.2	35.9	43.8	23.5	62.9	126.8	157.8	267.2	204.7	220.4	205.5	1,492.7
1913	142.0	123.0	89.8	89.0	49.9	149.7	160.5	259.9	324.5	258.1	205.6	179.6	2,031.6
1914	120.1	86.2	61.1	47.4	94.0	169.7	448.3	442.1	361.0	298.6	299.3	312.8	2,740.6
1915	219.9	161.4	158.1	130.6	83.4	57.8	241.3	241.4	359.2	222.5	156.1	131.5	2,163.2
1916	112.9	75.2	55.7	40.1	35.8	45.6	135.2	241.4	185.6	196.6	139.6	111.1	1,374.8
1917	89.2	58.8	32.3	16.6	19.9	31.7	76.3	316.7	275.9	175.6	132.2	101.8	1,327.0
1918	122.0	77.1	55.7	23.8	48.1	89.0	217.7	293.3	185.6	173.9	218.5	183.2	1,687.9
1919	121.9	84.4	102.5	92.6	88.8	125.4	266.6	233.1	426.9	335.9	258.9	179.5	2,316.5
1920	205.5	139.5	88.0	54.6	58.8	155.0	179.0	385.3	261.9	230.6	187.4	135.1	2,080.7
1921	94.7	73.4	50.3	25.7	44.7	142.8	269.9	246.5	218.5	154.4	130.4	114.7	1,566.0
1922	76.5	45.9	28.8	72.7	76.4	82.1	189.1	151.1	128.3	154.5	110.2	68.4	1,184.0
1923	71.0	89.9	80.8	49.1	28.8	71.6	185.9	345.1	270.6	245.2	192.8	187.0	1,817.8
1924	129.2	110.1	64.7	58.2	41.1	26.5	295.1	234.8	220.3	193.4	135.9	109.2	1,618.5
1925	80.1	51.4	35.9	40.1	102.9	89.0	234.6	308.3	274.1	258.1	187.4	148.1	1,810.0
1926	123.8	82.6	107.8	114.3	116.9	102.9	338.9	276.6	341.8	277.6	213.1	225.8	2,322.1
1927	160.1	106.4	84.5	58.2	32.3	36.9	158.9	174.5	249.8	177.1	119.4	153.6	1,511.7
1928	112.9	82.6	52.1	41.9	65.8	52.5	174.0	288.3	281.1	222.5	202.0	159.1	1,734.8
1929	105.5	84.4	64.7	58.2	92.3	85.6	157.2	161.2	202.9	282.4	192.8	146.2	1,633.4
1930	109.2	80.7	59.3	70.9	81.6	92.5	182.4	196.3	143.9	204.7	179.9	150.0	1,551.4
1931	185.6	163.3	125.8	264.5	173.4	158.4	209.3	218.0	176.9	139.1	104.7	129.6	2,048.6
1932	96.4	122.9	91.7	60.0	60.5	61.2	145.4	305.1	499.8	303.5	218.5	212.9	2,177.9
1933	152.8	104.6	68.2	34.7	18.2	66.4	115.1	147.9	130.0	177.1	117.5	77.8	1,210.3
1934	63.8	40.4	32.3	65.5	72.8	83.8	110.0	131.1	100.5	84.6	73.5	53.7	912.0
1935	48.9	61.0	47.4	29.7	31.5	115.8	142.0	228.8	303.5	233.1	180.5	159.0	1,581.2
1936	118.3	77.1	86.2	56.5	92.2	61.3	160.5	157.8	392.2	263.0	229.5	175.9	1,870.5
1937	127.4	99.1	66.4	43.7	35.8	61.3	100.0	142.8	222.0	217.6	181.8	220.3	1,518.2
1938	178.3	126.6	95.2	74.6	55.2	149.7	298.5	221.4	294.9	211.1	152.4	129.6	1,987.5
1939	147.4	82.6	64.7	72.7	62.3	99.4	162.2	224.7	157.8	149.6	179.9	137.0	1,540.3
1940	116.5	84.4	61.1	40.2	90.5	118.5	165.6	249.8	196.0	227.3	200.1	151.8	1,701.8
1941	156.5	137.6	111.4	183.1	226.3	243.5	337.2	376.9	534.6	472.0	332.3	270.3	3,381.7
1942	191.0	128.4	82.7	74.6	48.1	80.3	131.9	218.0	199.5	180.4	135.9	153.6	1,624.4
Total	4,978.4		3,351.1		3,293.9		13,894.4		12,108.0		8,416.4		
	6,701.6		3,692.1		3,309.8		12,084.1		14,654.3		9,765.6		98,449.7
	124.1	92.2	68.4	62.1	65.0	98.0	223.8	257.3	271.4	224.2	180.8	155.8	1,823.1

Table 3--Average monthly amounts on watershed between Fort Quitman and Upper Presidio

Month	54-year period 1889 - 1942					1939 - 1942
	Water dissipated		Rainfall	(T-40°)		Pan-evaporation
	Uplands	Valley-floor	Watershed averages			
(1)	(2)	(3)	(4)	(5)	(6)	(7)
	in	in	in	in	°F	in
Jan.	0.79	1.42	0.81	0.33	6.5	3.23
Feb.	0.59	1.39	0.61	0.24	11.7	5.56
Mar.	0.44	1.63	0.47	0.26	17.7	8.96
Apr.	0.40	2.59	0.45	0.48	25.4	12.28
May	0.42	4.36	0.52	0.60	33.7	14.34
June	0.62	5.77	0.76	1.14	41.1	14.82
July	1.43	6.64	1.57	3.06	41.7	12.80
Aug.	1.64	6.42	1.77	2.45	40.7	11.20
Sep.	1.74	5.36	1.83	1.99	34.9	8.64
Oct.	1.44	3.95	1.50	0.92	26.3	6.52
Nov.	1.15	2.43	1.19	0.42	14.7	3.82
Dec.	1.00	1.78	1.02	0.53	6.3	2.48
Total	11.66	43.74	12.50	12.37	300.7	104.65

$$Ru' = 156{,}649.15\,(0.38r_0 + 0.2r_1 + 0.13r_2 + 0.1r_3 + 0.08r_4 + 0.05r_5 + 0.04r_6 + 0.02r_7) \quad (22)$$

To save space, the table of such calculated values is not shown here.

(39) If then we subtract from each monthly value in the table just mentioned the corresponding monthly value of Y, computed by equation (20)--these values will be found in [7]--we will obtain the values shown herewith in Table 2. These values are monthly values of Du, computed in accordance with equation (21), or

$$Du = (Ru' - Y) \quad (23)$$

(40) Substitute in equation (23) the values of Y and Ru' from equations (20) and (22), respectively, and then

$$Du = (156{,}649.15 - K - 0.08333k)\,(0.38r_0 + 0.2r_1 + 0.13r_2 + 0.1r_3 + 0.08r_4 + 0.05r_5 + 0.04r_6 + 0.02r_7) - 0.00917r^2k \quad (24)$$

(41) According to equation (24), Du depends on a set of monthly constants and coefficients and upon the average depth of rainfall on the watershed.

(42) From equations (18) and (24), and from paragraphs (34) and (41) there have been shown the fundamental data which approximately control or determine the amounts of water dissipated into the air each month from the valley-floor and from the upland of the Rio Grande Watershed from Fort Quitman to Upper Presidio. Tables 1 and 2 show these monthly values for the past 54 years. It should be noted that these amounts of dissipation are not controlled by temperature, wind, or humidity as might ordinarily be expected, but only slightly and indirectly through I and L. The dissipation is controlled by the supply of dissipatable water. This situation is similar to that of silt-transportation by rivers, which is frequently controlled by the supply of silt rather than the transporting power of the current.

(43) From the totals of Tables 1 and 2 there have been compiled the figures in the first four columns of Table 3 showing the 54-year average monthly amounts of water dissipated on the entire watershed from Fort Quitman to Upper Presidio. The 54-year rainfalls and temperatures are from [5] and [2]. The pan-evaporation figures are the approximate averages over the watershed for the period 1939 to 1942, and are taken from the Ysleta and Presidio records as shown in [8].

(44) The monthly values from Table 3 are represented by the six curves on Figure 3. The most interesting comparison with respect to magnitudes and pattern is that of the curve showing pan-evaporation and that showing total water dissipated. Their minima occur four months apart

and their maxima three months apart. The average annual depth of pan-evaporation is eight times the average annual total dissipation and over twice that on the valley-floor.

(45) Since this paper barely scratches the surface of the subject presented, it is hoped that others will express themselves, to the end that, from a composite of experiences of various interested persons in different localities, climatological data may be presented in a more usable form.

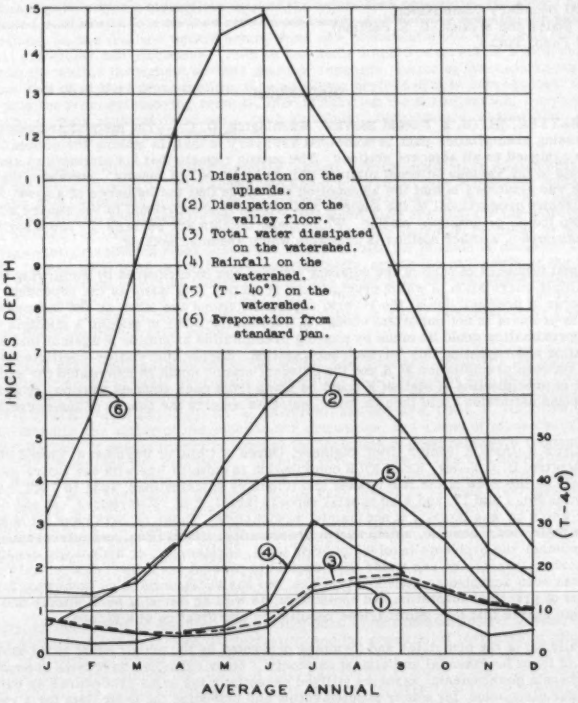

INCHES DEPTH
(T - 40°)
(1) Dissipation on the uplands.
(2) Dissipation on the valley floor.
(3) Total water dissipated on the watershed.
(4) Rainfall on the watershed.
(5) (T - 40°) on the watershed.
(6) Evaporation from standard pan.
J F M A M J J A S O N D
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Fig. 3--Average monthly values for dissipation of water, rainfall, and evaporation on watershed between Fort Quitman and Upper Presidio

References

[1] Water Bull. No. 9, p. 95, No. 10, p. 97, and later data and index in files of International Boundary Commission.
[2] Water Bull. No. 12, p. 95.
[3] Water Bull. No. 12, p. 46 et. seq.
[4] Water Bull. No. 12, p. 96.
[5] Water Bull. No. 12, p. 84.
[6] Water Bull. No. 12, p. 60.
[7] Water Bull. No. 12, p. 50.

[8] Water Bull. No. 12, p. 94.
[9] Trans. Amer. Soc. Civ. Eng., v. 107, p. 1243, 1942.
[10] Water Bull. No. 10, p. 80, and Water Bull. No. 9, p. 49 and Figure 1 of this paper.
[11] Water Bull. No. 10, p. 79.

Note: The Water Bulletins are published annually by the United States Section of the International Boundary Commission, United States and Mexico.

International Boundary Commission,
United States and Mexico (U. S. Section),
El Paso, Texas

DISCUSSION

R. H. BLYTHE, JR. (U. S. Forest Service, Washington, D. C.)--The method proposed for estimating missing precipitation-data is somewhat arbitrary in that, in making the estimate, equal weights are assigned to all adjacent stations. The author reports that his attempts to assign different weights to the various adjacent stations did not improve his results. However, the method of weighting was arbitrary in that the assumption was made that the influence of a given adjacent station is directly proportional to the angle A and inversely proportional to the square root of its distance from the X, or unknown, station. While these weights are perhaps the most logical that could be "assumed", another method is available which assumes nothing.

The actual influence of each of the adjacent stations can be measured by employing the technique of multiple correlation in which precipitation at station X is taken as the dependent variable and the records of precipitation at the several adjacent stations are taken as the independent variables. If the problem is not important enough to warrant the labor of making a multiple correlation-study, an approximation could be made by plotting precipitation at station X against that at a single adjacent station and repeating this for each such station. Simple correlation-coefficients for the correlation between precipitation at X and the adjacent station could be calculated for each station. An estimate of precipitation at station X could be made from each adjacent station. A weighted average of these estimates could then be made, using as weights the square of the correlation-coefficients.

CLARENCE S. JARVIS (Senior Civil Engineer, Office of Chief of Engineers, United States Army, Washington, D. C.)--Mr. KEELER'S contribution is quite in line with the entire series of yearly reports on the Flow of the Rio Grande and tributary contributions, 1931 to 1942, comprising Water Bulletins No. 1 and 12, and also special reports [see 1, 2 of "References" at end of discussion] for which he was largely, if not mainly, responsible. Those reports have all been characterized by their clear, concise, authoritative presentation, illustration, and interpretation of basic data, whether the problems involved strictly legal, engineering, or hydrologic questions, or some combination thereof. He has never been content to present his subject-matter only according to what has been accepted as standard practice, but has endeavored to go somewhat farther into the fields of practical adaptation and application, as well as devising such simple and well-chosen graphic charts that they summarized results for clarification at a glance.

Practically all of the principles and formulas presented by the author seem to be basically sound, most of them fundamental and almost axiomatic. Many examples have been encountered by the writer wherein governmental agencies utilized essentially the same procedures as outlined in the paper under discussion, for either supplementing and extending the basic data for a region or for a particular station, or occasionally for correcting some record that has been challenged as obviously erroneous. An example is afforded by an assembly of data [3] treated by the writer under the guidance of an official climatological specialist for the purpose of making such a correction; ordinarily the objective was extension of the data.

The author's Tables 1 and 2 should stand as monuments to his earnest endeavors to bring forth the most valuable information that the basic data can be made to yield. Likewise, the three Figures present unassailable information as to (1) the nearly normal precipitation-depths for the seven-year period, 1935-1942, (2) the dissipation of flood-peaks of 1932 as a result of valley-storage along the lower Rio Grande and also the outstanding peaks attained and volume delivered during the year 1942, and (3) the great discrepancy between evaporation-losses from a standard pan as compared with the dissipation from the surface of either the uplands or the valley-floor. The inclusion of the curve showing monthly rainfall on the watershed helps to explain the other

curves in Figure 3. It is quite evident that the very steep gradients and well-developed drainage-systems of the uplands incline to reduce the time when dissipation can proceed at full pace, while the flat gradients and resulting sluggish movements along the valley-floor, together with higher temperatures, less rainfall, and less obstructions against wind-movement all conspire to increase the losses into the atmosphere from the valley-floor, thus attaining nearly four times the losses sustained on the uplands as shown in Table 3, or as 43.74 is to 11.66 inches depth. In contrast, average annual evaporation from a standard metal pan was 104.65 inches, with constant exposure.

With the engineer-lawyer's meticulous regard for established procedure, the author has adhered to accepted methods so long as they seemed adequate. For broader and also for more detailed applications, he has inclined toward establishing new precedents, of course with due regard to fundamental principles and processes. Thus he has made notable progress in a field more or less familiar to the writer throughout several years of research, including the assembling of all pertinent basic data of evident dependability, then supplying derived data to correct local deficiencies by interpolation from neighboring records, then integrating the entire series, comparing and coordinating the various physical phenomena, such as rainfall, temperature, evaporation, infiltration, and finally the runoff-rates and volumes.

A definite concept guiding the writer's efforts through several successive assignments included use of the monthly records, thus assembled and compared, to give acceptable approximations to missing data pertaining to any of the main physical phenomena [4, 5, 6, 7, 8]. Inasmuch as stream-discharge data are generally the least in evidence, they are also the ones ordinarily derived from related records. Always, proof of such derivations should be required by testing out the adopted formulas or assumed relationships on observed data for periods of complete concurrent records. Unless such tests are withstood satisfactorily, either the basic data or the assumed formulas and relationships should be subjected to further study until the disturbing differences are reconciled. Examples of such reconciliations are afforded in recent technical publications of the writer's, in some instances involving wide abnormalities in either temperature or local rainfall to account for the seemingly erratic runoff [9, 10, 11].

As a result of such studies conducted by the writer with primary objectives including the assembly and supplementing of basic hydrologic information by all available and logical means, also his realizing the outstanding importance of recent contributions from such leaders in this field as Drs. C. W. THORNTHWAITE and ROBERT E. HORTON, and Messrs. GAIL A. HATHAWAY and MERRILL BERNARD, the author of the paper under discussion, and a host of others with pioneer leanings and initiative, it seems timely to suggest the inclusion of comprehensive research projects of this character among postwar programs. Granting that such estimates and derivations of stream-discharge and related data cannot take the place of actual observations and measurements, they seem to be the best available substitutes, having been tested on various river-systems representing wide ranges of climatic and other physical conditions with consistently encouraging results. THORNTHWAITE, for example, determines by workable formulas what the evaporation- and transpiration-losses must be, on the basis of temperature, prevailing humidity, wind-movement, and other items of record. Average annual precipitation minus the designated losses, month by month, with due regard to required time of travel, have given runoff-hydrographs that follow the graphs of observed mean record-discharges so closely as to be very encouraging.

Naturally, in the course of mending the missing data, actual measurements govern the whole operation by doing double duty in both the derivation and the checking of formulas or other expressions of relationships among basic hydrologic data, whereby the unknown may be derived, estimated, or approximated outside the limits of fully concurrent record. Thus, the recent impetus in extending nets for the procurement of hydrologic data has unlocked the doors leading to rich returns in the interpretations of partial data in such a manner as to approach factual data more or less closely, as abundantly demonstrated.

As noted in a current paper by the writer and scheduled for presentation before one of the sections of the American Geophysical Union during this annual meeting, several foreign investigators undertook to solve the problems of mean annual discharge for selected rivers all over the Earth's surface shortly before and after the turn of the century. At what point in the development of hydrologic science did those ventures change from insecurely founded "guesstimates" to well-founded, logical derivations? The answer is not difficult: It happened only after the actual gagings had become sufficient in number and in distribution to establish and to test the formulas and assumed relationships. For many of the foreign rivers, the transition-period was subsequent to 1912; for others, after 1920 or even 1930.

Table 1--Precipitation - and runoff - characteristics of selected rivers in various continents

No.	River and gaging station	Main channel length	Drainage area	Mean annual			Runoff factor	Pct mean represented by		Variability
				Precipitation	Runoff			Minimum	Maximum	(max/min)
				P	R		R/P=F			=V
		miles	sq.mi.	in	in	cfs	pct	pct	pct	
1	Yukon, Eagle, Alaska	880	122,000	13.0	8.5	76,000	65	14	420	30
2	Yukon, mouth, Alaska	2,300	330,000	14.0	9.0	218,000	64	15	375	25
3	Mackenzie, mouth, Can.	2,868	677,400	18.0	12.0	600,000	67	20	320	16
4	Churchill, mouth, Can.	650	77,000	15.0	8.0	45,000	53	12	480	40
5	Winnipeg-Nelson, mouth, Can.	1,660	370,800	20.0	6.6	180,000	33	20	340	17
6	Niagara, Niagara, Can.	1,100	263,500	31.0	9.8	190,500	32	61	127	2
7	St.Lawrence, mouth, Can.	1,900	565,200	35.0	12.5	520,000	36	36	220	6
8	Ohio, Cairo, Ill.	1,300	203,900	44.2	18.3	274,000	41	9	675	75
9	Missouri, mouth, Mo.	2,900	531,400	20.7	1.9	74,400	9	5.7	810	142
10	Missouri, Fort Benton, Mont.	470	24,600	16.0	4.5	8,200	28	3.9	1,704	437
11	Columbia, Grand Coulee	400	74,100	33.0	19.8	107,700	60	14	459	33
12	Columbia, The Dalles, Ore.	1,050	237,000	24.0	11.4	199,000	48	18	595	33
13	Columbia, mouth, Ore.	1,270	298,000	29.0	14.4	316,000	50	20	400	20
14	Sacramento, mouth, Calif.	300	28,000	24.5	8.7	18,000	35	7	3,000	429
15	San Joaquin, mouth, Calif.	260	18.178	16.0	4.5	6,000	28	3	1,500	500
16	Humboldt, Palisade, Nev.	90	5,010	12.5	0.9	326	7	0.6	1,330	2,220
17	Provo, Vivian Park, Utah	60	600	19.0	8.1	357	43	14	890	64
18	Colorado, Grand Canyon	620	138,700	14.0	1.7	17,300	12	4.0	1,270	318
19	Colorado, Yuma, Ariz.	1,060	244,800	13.0	1.3	22,800	10	2.4	1,050	438
20	Gila, Coolidge Dam, Ariz.	230	12,880	11.8	0.49	468	4	0.1	27,800	278,000
21	Rio Grande, San Marcial, New Mexico	400	24,200	12.8	0.84	1,500	7	0.1	3.330	33,300
22	Rio Grande, Rio Grande, Tex.	1,600	174,200	14.6	0.56	7,100	4	13.3	2,800	210
23	Colorado, Austin, Tex.	380	38,160	24.0	1.0	2,720	4	0.5	17,700	35,400
24	Brazos, Richmond, Tex.	620	44,050	27.0	2.2	7,210	8	0.5	1,660	3,320
25	Trinity, Romayor, Tex.	350	17,190	34.0	5.2	6,510	15	2.0	1,246	623
26	Mo.-Miss.,mouths, La.	4,220	1,244,000	30.1	6.9	635,000	23	15.8	386	24
27	Tennessee, mouth, Ky.	870	40,320	50.0	22.9	68,000	46	7.0	676	97
28	Potomac, Washington, D.C.	260	11,560	34.8	13.3	11,260	38	4.0	4,300	1,075
29	Santee, Ferguson, S.C.	270	14,800	47.6	17.0	18,460	36	13.9	2,000	144
30	Suwanee, Ellaville, Fla.	120	6,580	49.8	12.2	5,900	24	17.0	1,240	73
31	Chagres, Gatun, Panama	60	1,320	110	73	7,100	66	6	1,800	300
32	Magdalena, mouth, Colum.	950	130,000	54	18	172,000	33	17	1,400	82
33	Orinoco, mouth, Venez.	1,700	430,000	52	17	538,000	33	19	960	51
34	Amazon, mouth, Brazil	4,100	2,772,000	64	19	3,960,000	30	26	230	9
35	La Plata, mouth, Argent.	2,400	1,486,000	47	17	1,860,000	36	20	400	20
36	Niger, mouth, Africa	2,600	980,000	54	19	1,370,000	35	12	300	25
37	Congo, mouth, West Africa	2,900	1,425,000	56	16	1,670,000	29	14	240	17
38	Orange, mouth, South Africa	1,300	400,000	11	1.4	41,000	13	4	800	200
39	Zambesi, mouth, East Africa	1,600	514,000	49	14	529,000	29	7	350	50
40	Nile, Cairo, Egypt	3,800	1,290,000	32	1.2	114,000	3.7	3	480	160

Table 1--Precipitation - and runoff - characteristics of selected rivers in various continents--Concluded

No.	River and gaging station	Main channel length	Drainage area	Mean annual Precipitation P	Mean annual Runoff R		Run-off factor R/P=F	Pct mean represented by Minimum	Pct mean represented by Maximum	Variability (max/min =V
		miles	sq.mi.	in	in	cfs	pct	pct	pct	
41	Jordan, mouth, Palestine	340	7,000	16	3.7	1,900	23	6	1,800	300
42	Euphrates, Basra, Iraq	1,600	430,000	13.4	1.9	60,000	14	2	600	300
43	Amu Darya, Aral Sea	1,500	440,000	9	0.8	26,000	9	1	460	460
44	Ganges-Brahmaputra, India	1,680	588,000	72	29	1,260,000	40	4	240	60
45	Irrawaddy, Rangoon, Burma	1,240	158,000	55	26	302,000	47	20	800	40
46	Murray, Adelaide, Australia	1,170	412,000	17	1.4	42,000	8	3	900	300
47	Brisbane, Brisbane, Australia	125	5,300	46	18	7,000	39	4	960	240
48	Yangtze, mouth, China	3,100	689,000	37	14	710,000	38	7	300	43
49	Hwang-ho, mouth, China	2,700	387,000	22	3.4	97,000	15	3	480	160
50	Amur, mouth, Siberia	2,900	403,000	16	2.7	80,000	17	6	720	120
51	Lena, mouth, Siberia	2,860	896,000	11	2.7	178,000	25	18	470	26
52	Yenisei, mouth, Siberia	2,800	980,000	9	2.9	209,000	32	14	420	30
53	Ob, mouth, Siberia	3,200	1,125,000	10	2.9	240,000	29	16	480	30
54	Ural, mouth, Russia	1,400	90,000	16	3.6	24,000	23	7	600	86
55	Volga, mouth, Russia	2,300	592,000	17	3.8	166,000	22	8	480	60
56	Thames, London, England	106	3,800	24	8.6	2,400	36	17	1,400	82
57	Shannon, Limerick, Ireland	140	4,540	44	21	7,000	48	20	800	40
58	Rhone, France	350	37,000	40	22	59,000	55	24	710	30
59	Po, Italy	300	27,400	44	27	55,000	61	15	636	42
60	Danube, Roumania	1,700	316,000	30	9.2	215,000	31	30	279	9

Note: Data for Table 1 were assembled from every available source, and subjected to such revisions as seemed to be required in view of later or more authoritative references; many of the items involved estimates or approximations, and may be changed materially by new accessions of records or by revised evaluations.

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[5] DE SOUSA SILVESTRE, Descriptiva das Bacias Hydrografica do Amazon e da Prata, 1923 (Library Congress, No. GB1263 S6, 1923).
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As a direct result of recent releases, mainly in foreign technical literature, together with methodical gleanings of related data over a period of more than 20 years, the writer finds it possible and timely to release the recently completed compilations of rainfall- and runoff-data pertaining to selected river-systems of all continents, as shown in Figure 1 and Table 1 submitted herewith. These represent but samples of what could be supplied were it not for wartime restrictions applying to certain areas. A textual discussion of this assembly of hydrologic data is scheduled for release in a forthcoming issue of a scientific monthly magazine. However, the figures and tabulations were intended to tell their own stories to those familiar with the general problems.

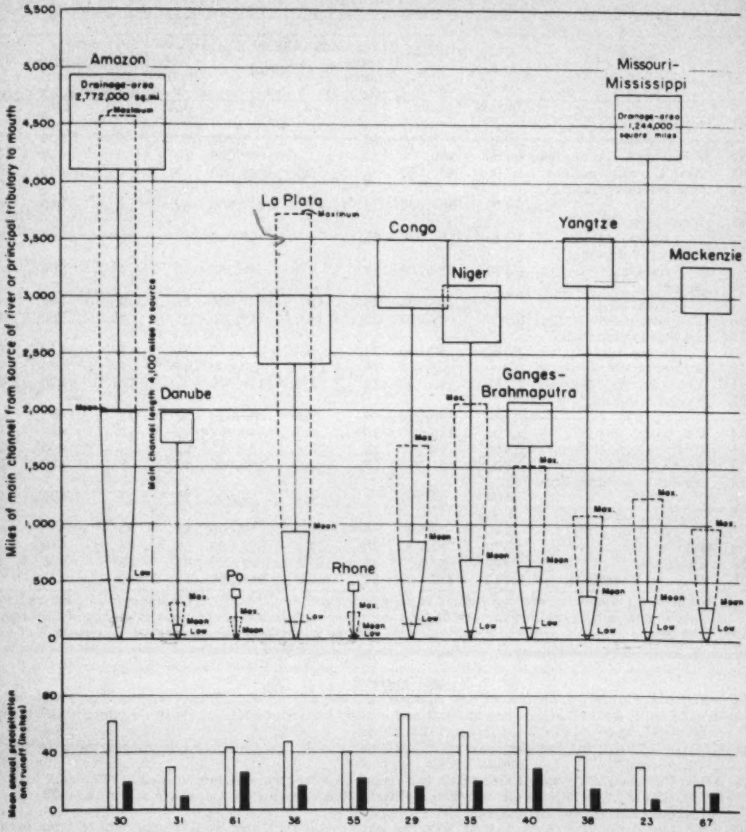
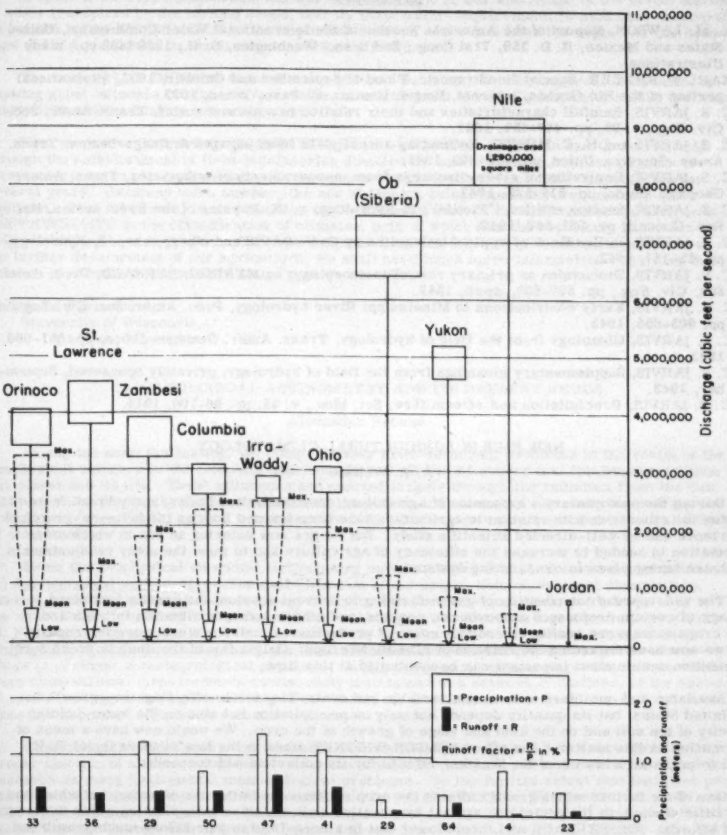


Fig. 1--Graphic presentation of physical and

Because Mr. KEELER'S paper should meet some of the present-day needs in a broad, inviting field, it seems desirable to suggest slight revisions of nomenclature employed in the numerous formulas, in order to conform as closely as practicable to standards already in vogue among hydrologists and engineers. For example, it seems important to retain the symbols P, R, and E to represent precipitation, runoff, and evaporation in whatever units may be adopted for a given discussion. Now, if it seems desirable to express results alternately in inches and acre-feet, it would be quite suggestive and therefore helpful to the reader's memory to introduce the double prime (") following each symbol to designate inches, or the subscript $(_{a\text{-}f})$ to indicate that the units have been converted into acre-feet. Likewise, the basic data for individual stations and for separate years could well continue with their well-chosen accents and subscripts defining the



hydrologic characteristics of selected rivers

complete series; but the composite average for an entire basin throughout the entire period of observed and derived record could be emphasized by a suggestive subscript, such as ($_{Ave}$) or a circle ($_{o}$) indicating its all-inclusive character. Special attention to such minor details might readily reduce the number of separately listed symbols and thus assist the casual reader to a clearer grasp of the essentials, so that "he who runs may read" and understand.

Mr. KEELER'S latest contribution is a fitting climax to the series of workable innovations and ideas that have characterized the reports and bulletins for which he has been responsible within the past 15 years, and his earlier years of professional practice of which the irrigation-systems with which he was identified and associated constitute the record.

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NEW JOBS IN AGRICULTURAL CLIMATOLOGY

A. R. Whitson

During the past century's expansion of agriculture over the United States, many broad facts regarding the climate and its relation to agriculture have been learned both by the farmers' practical experience and by well-directed scientific study. But we are now entering an era in which more information is needed to increase the efficiency of agriculture and to meet the many readjustments which are taking place in our farming systems.

The wide-spread introduction of grass-farming to prevent erosion, the greatly increased acreage of certain crops such as soybeans, peanuts, and others and specialization in truck and fruit crops to improve quality and reduce costs of production all call for much more information than we now have regarding the relation of climate to crops. Only a few of the lines in which such information seems most important can be mentioned at this time.

Available soil-moisture is the most variable and controlling factor affecting crop-growth in the United States, but its quantity depends not only on precipitation but also on the water-holding capacity of the soil and on the kind and stage of growth of the crop. We would now have a mass of information on this matter if the effort MILTON WHITNEY made in the late nineties to get F. H. KING to organize a branch of the Weather Bureau for its collection had succeeded.

One of the factors which greatly affects the crop's efficiency in the use of water, but which has been little studied, is the protection against evaporation and excessive transpiration which the crop itself affords. KIESSELBACH at Lincoln found that in a corn-field in June before much growth had occurred, evaporation from jars ten feet above the ground was only 1.7 times that at six inches while in August it was 5.2 times as great. Preliminary observations by the writer during a hot, dry period in early August showed that the soil-moisture on a harvested oat-field was at the wilting-point with clover-seeding killed, and the temperature at four inches was 95° at 4 p.m. while under a dense two and one-half foot stand of soybeans the temperature was 76°--practically the average day and night temperature of the preceding ten days--and the moisture-content was abundant for continued growth. The soybeans had already taken much more water from the soil than the oats had but the lower soil-temperature increased capillarity and prevented soil-evaporation, thus making available the precipitation of the preceding month.

The relation of temperature to respiration and photosynthesis which determines the loss or storage of starch and sugar in several crops is one of the chief factors in determining their yields but has received little careful study. The work of JOHN BUSHNELL on potatoes is clear evidence of the importance of this matter.

In spite of the very considerable amount of research on it, our knowledge of the actual amount of water transpired by the various crops, that is, their water-requirement, is still very inaccurate as pointed out by KIESSELBACH. One important cause of error has been the neglect of the influence of field-conditions on temperature previously mentioned.

The work of J. G. DICKSON of the Bureau of Plant Industry, but working from Wisconsin, is showing great influence of climatic factors on the malting and brewing qualities of barley for which nearly fifty million bushels are being used.

What the writer just now wants to do is to point out that these problems can be solved only through the establishment of field-laboratories directed by men trained in both the physics of meteorology and in plant-physiology. European countries have had such field-laboratories for several years. Germany has a number, the one at Munich being especially well manned and equipped. This, of course, is no reflection on the splendid work of KINCER and associates or of THORNTHWAITE in the classification of climates, both of which are the necessary bases for the kind of studies above suggested. But if governmental agencies are to give adequate guidance in the further development of our agriculture, we shall need much more information regarding the relation of climate to the various crops than we now have.

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CLIMATOLOGICAL ACTINOMETRY AND ITS PRESENT NEEDS

Alexander Breese

Among the most fascinating, yet comparatively little-advanced, problems in the realm of the geophysical sciences is the complete understanding of all the influences that the Sun exerts upon our planet and its life. These influences are exerted largely through the radiation from the Sun intercepted by the Earth; the determination of the nature and amount of this radiation and its distribution over the Earth, and the investigations of its effects, are comprised in the general subject of actinometry.

From the geophysical viewpoint, actinometry may be divided into the following subdivisions: (1) Astrophysical actinometry--The determination of the origin, nature, spectral composition, amount, and distribution of radiant energy from the Sun (and other extraterrestrial sources) at the outer limit of the Earth's atmosphere (an astronomical, rather than a geophysical, problem). (2) Physical actinometry--The determination of the transformations of radiant energy during propagation through the atmosphere, and their effects in the physical phenomena of the atmosphere (a problem of meteorological physics). (3) Climatological actinometry--The determination, from observational measurements continuously maintained at a network of stations, of the amount of radiant energy reaching the surface of the Earth, its distribution over the Globe and its variations (an important element in a complete climatic record).

Climatological actinometry has long been internationally recognized as an appropriate and proper function of a meteorological service; and physical actinometry is necessarily involved in research on many fundamental meteorological problems. To the limited extent that facilities permitted, work in these subjects has been conducted by the United States Weather Bureau ever since 1901 under the name of "solar radiation investigations" [see IRVING F. HAND, Review of United States Weather Bureau solar radiation investigations, Mon. Weath. Rev., v. 65, pp. 415-441, 1937]; this name, however, is somewhat misleading, and the actual character of the work is more accurately indicated by the terminology used above.

Considered as a climatological factor, the solar radiant energy that reaches the surface of the Earth is characterized by diurnal and seasonal variations in amount and now and then by long-time trends, by irregular variations with changing weather-conditions, by variations in spectral composition depending upon the state of the atmosphere, and by very great geographical differences in all these characteristics, often depending upon highly local conditions. Only by actual observations can these characteristics be determined; and an adequate amount of data has never been available. Actinometric stations have been widely scattered and unevenly distributed over the Globe, while the observational data are in many cases meager and in a large part not readily accessible. In an effort to make existing data more widely available, the International Meteorological Organization has designated a number of institutions to serve as regional clearing-centers and to establish

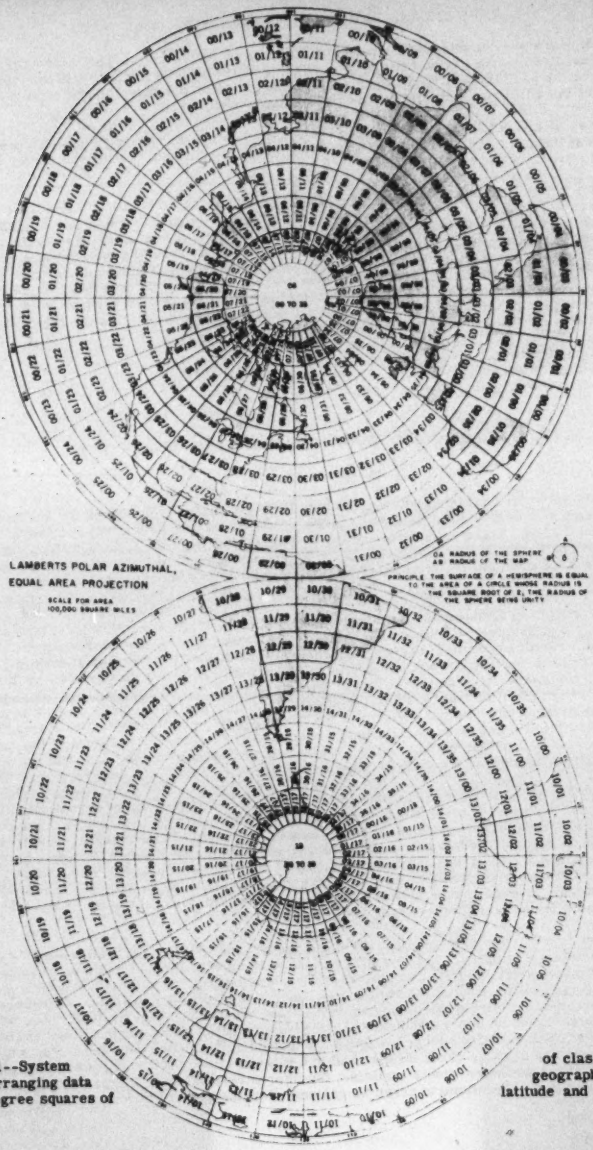
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Fig. 1--System of classification for arranging data geographically in 10-degree squares of latitude and longitude

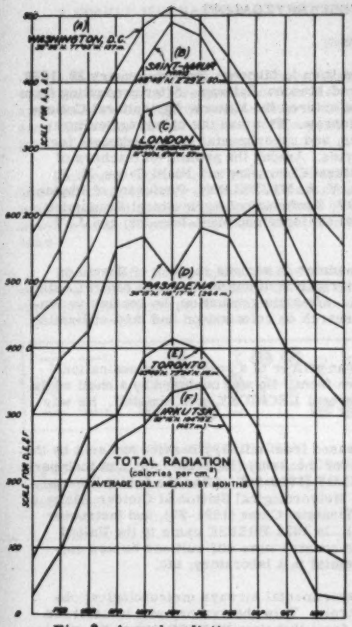

Fig. 2--Annual radiation-curves

actinometric bulletins for the publication of data, but these centers are comparatively few and mostly confined to middle latitudes of the Northern Hemisphere. Such data as may exist for large parts of the Globe, if published at all, are scattered through many local publications of small circulation, some no longer are issued and are usually limited to monthly means and annual summaries, while many data known to exist are practically unobtainable. Furthermore, the destruction and disturbed conditions throughout the world resulting from the present war have endangered the safety of accumulated data, the continuity of observations and of publications, and even the existence of many stations.

In order to be able more effectively to meet the requests for actinometric data and information that are received by the Weather Bureau--many of them for war purposes--the Bureau has begun the construction of a system of files and indexes which, when completed, should make it possible to quickly locate all data available for any specified location on the Earth, and all information of importance on any problem of actinometry or its practical applications.

In this extensive and complicated task, one of the first difficulties encountered is the problem, common to all climatological work, of the system to be used in classifying and arranging data for filing purposes, whether, for example, geographically by countries, with the disadvantages arising from the many successive changes in political dependency, or alphabetically by stations, even though frequent changes occur in names of stations, or in some other manner. The method finally adopted as the most convenient and efficient for radiation-data is to file the data by ten-degree squares of latitude and longitude. To facilitate finding all available data for any given area, including ocean areas, each square is identified by an index-number, constructed as follows: Each hemisphere is divided into nine latitude-zones, which, beginning at the equator, are numbered from 00 to 08 in the Northern Hemisphere, and from 10 to 18 in the Southern Hemisphere. The Earth is further divided into 36 longitudinal sectors, numbered eastward, beginning at the Greenwich meridian, from 00 to 35. A unique number for each ten-degree square is then formed by combining the zone-number and the sector-number, separated by a slant line; thus 03/08 indicates the square between latitudes 30° and 40° north and longitudes 80° and 90° east. A station at latitude 23° south and longitude 68° west would be in the square 12/29.

On a large-scale map of the world, these index-numbers are entered in each square, and the locations of all stations at which actinometric observations are known to have been made at any time are plotted. For each station, a form is filled out, giving a brief description of the station, the period during which it operated, the types of observations taken, and a general indication of where the data may be found; these forms are placed in a file arranged according to the index-numbers of the ten-degree squares. The information in this file will be amplified by appropriate further files, indexes, and annotated bibliographies that will collectively enable all available data, appropriate for any given purpose, to be quickly located, without inconvenience or error from uncertainty of station-names, confusion in political dependency, or complexities of the system of classification.

The larger part of the task of searching meteorological and other scientific literature, and assembling the material from published and unpublished sources to complete these files in the way that has been planned, still remains to be accomplished. It is hoped that in this way there may eventually be assembled in at least one place in the United States a complete set of existing actinometric records, in easily usable form.

U. S. Weather Bureau,
Washington, D. C.

OBITUARY, ALEXANDER A. BREESE (BRYZGALOV)

Basil M. Bensin

ALEXANDER A. BREESE (A. A. BRYZGALOV) was born in Moscow, Russia, January 29, 1888. His father was a civil engineer employed on the Petrograd-Moscow Railway. After graduating from the private Real High School of Voskresensky in 1908, he entered the Moscow Agricultural College located in Petrovsko-Razumovskoye in the suburbs of Moscow. This was the oldest agricultural college in Russia with the best laboratories, greenhouses, and experimental field-equipment for studying all branches of agriculture, forestry, and fisheries. Among the prominent teachers of BREESE were I. PRIANISHNIKOV, Professor of Agricultural Chemistry and Field Crops, V. R. WILLIAMS, Professor of Soils, Irrigation, and Drainage, V. A. MICHELSON, Professor of Physics who constructed an actinometer, and A. F. FORTUNATOV, Professor of Agricultural Economics. His classmates were N. I. VAVILOV, famous agricultural explorer and plant-breeder, and A. V. CHAPANOFF, agricultural economist.

During his college course, BREESE worked every summer in various regions of Russia on sugar-beet plantations and, during several seasons, on irrigation of cotton-fields in central Asia. He was one of the pioneers of cotton-breeding in Russia. After his graduation, he became an employee of the Department of Agriculture in charge of research on colonization and land-utilization problems in central Asia.

During World War I, he joined the Russian Army as an officer of a special communication-unit in charge of automobile transportation on the western front. He was contused by a shell while driving a car containing a Russian Army commander, General LECHICKY, and his staff. He was awarded the St. George Cross.

After the first Russian Revolution BREESE was released from military service and sent by the Provisional Government to Mongolia for procuring meat for the Army (1917-19). He next took part in the Mongolian Exploratory Expedition of General KOZLOV (1919-20). After the Soviet Revolution he moved to China where he became Director of the Meteorological Station at Cicicar, Manchuria (1920). He was next manager of a dairy farm in Tientsin, China (1921-22), and Instructor in Economics at the Tientsin International College (1922). In 1922 BREESE came to the United States, entering at San Francisco. His first years in this country were difficult and he was employed in several capacities, working on a farm, as a chemist in a laboratory, etc.

In September, 1928, he was chosen to organize an experimental airways meteorological observatory for the Guggenheim Foundation at Lebec, California. This observatory was transferred to the United States Weather Bureau on July 1, 1929, and from that time BREESE was in the employ of the Weather Bureau. The observatory, however, was moved October 1, 1930, to Fresno, California, and in October, 1937, to San Francisco.

In August, 1942, BREESE was transferred from San Francisco to the main office of the Weather Bureau in Washington, D. C. Although he did not complete his original work in meteorology, he outlined a new and original aspect of meteorological studies of special value to aeronautics.

He was a broad-minded student of modern problems of climatology and physical geography. On the basis of careful study of the outstanding works in these fields in various languages, he built up his own hypotheses and theories of meteorology and climatology. There is no doubt that his contributions to the field of meteorology as well as those to Russian agriculture were original and outstanding.

BREESE possessed a charming personality and was always ready to assist his colleagues and collaborators. He was of the type of Russian scientist who is devoted to thoughtful studies and the solution of new problems on a world-wide scale.

He died suddenly of a heart attack at his home in Washington, D. C., May 20, 1944, leaving the elaborate plans for his meteorological work unfinished but distinctly outlined for future development.

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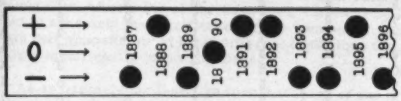
A SIMPLE MECHANICAL AID IN THE STATISTICAL ANALYSIS OF CLIMATIC DATA

Hans Neuberger

In the most primitive type of forecasting the statistical evidence gained from climatic interrelations is used to foreshadow seasonal features. This practice is not satisfactory if the physical causes for the empirical relationship is unknown. Yet the extrapolation of past climatic performance may serve useful purposes, especially if the expectancy of the foreshadowed event can be expressed quantitatively.

Statistical studies of climatic elements such as temperature, precipitation in general, and snowfall in particular, made at the Pennsylvania State College, have led to the development of a mechanical aid in the organization of the observational data on hand. The method, even though not novel in principle, is to my knowledge, new in its simplicity and its low cost, and operates as follows.

The climatic data, as, for example, the monthly precipitation-totals, are treated as members of one of three classes: Normal (0) (this class with a certain latitude), excessive (+), and deficient (-). As members of such classes the climatic data are represented on a strip of paper as holes whose position is significant of the class to which they belong. The sequence of holes represents the sequence of years for a given month, or the sequence of successive months for the whole period, successive seasons, etc. An example is given in Figure 1.



JANUARY PRECIPITATION

Fig. 1--Example of representation of climatic data as members of three classes: Excessive (+); normal (0); deficient (-)

In order to facilitate the punching of the holes, a special device was constructed which permits automatic spacing of the holes as well as the uniform

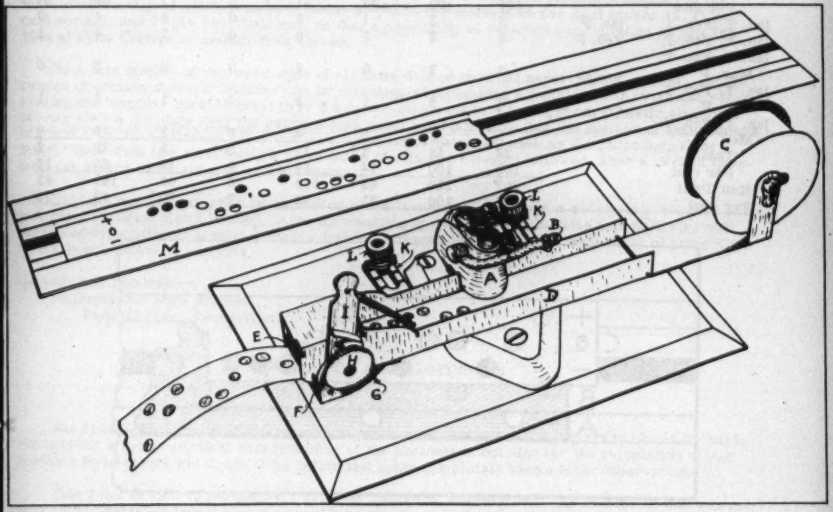


Fig. 2--Mechanical aid for statistical analysis

Table 1--Example of analysis

(C = Number of cases under conditions as stated and RC = number of cases under conditions reversed; T = temperature; P = precipitation)

Conditions				June precipitation					
Excessive	Deficient	C	RC	Excessive		Normal		Deficient	
				C	RC	C	RC	C	RC
....	Jan., Feb.	12	6	2	4	2	2	8	0
Mar.	Jan.	10	11	1	5	0	1	9	5
Apr.	Jan.	9	14	1	7	2	1	6	6
May	Jan.	11	12	2	8	2	2	7	2
Mar.	Feb.	11	9	3	5	1	3	7	1
Apr.	Feb.	3	9	0	3	0	2	3	4
May	Feb.	10	11	2	5	0	4	8	2
Mar., Apr.	....	6	12	1	6	1	2	4	4
Mar., May	....	8	14	1	7	0	4	7	3
Apr., May	....	9	16	1	8	2	4	6	4
Total		89	114	14	58	10	25	65	31
Per cent		100	100	16	51	11	22	73	27
Jan. T, Feb. T	....	10	8	3	4	0	2	7	2
Jan. T	Jan. P	11	7	4	5	1	0	6	2
Jan. T	Feb. P	12	7	4	2	1	2	7	3
Jan. T, Mar. P	....	9	8	2	3	0	1	7	4
Jan. T, Apr. P	....	4	10	1	5	0	1	3	4
Jan. T, May P	....	7	7	2	5	0	1	5	1
Feb. T	Jan. P	11	6	2	5	1	0	8	1
Feb. T	Feb. P	9	4	2	0	0	1	7	3
Feb. T, Mar. P	....	8	9	3	5	0	2	5	2
Feb. T, Apr. P	....	7	12	2	5	1	2	4	5
Feb. T, May P	....	8	12	1	7	1	3	6	2
Total		96	90	26	46	5	15	65	29
Per cent		100	100	27	51	5	17	68	32
Jan. T, Feb. T	Jan. P	5	2	1	2	0	0	4	0
Jan. T, Feb. T	Feb. P	5	2	1	0	0	1	4	1
Jan. T, Feb. T, Mar. P	.....	3	2	0	2	0	0	3	0
Jan. T, Feb. T, Apr. P	....	4	5	1	3	0	1	3	1
Jan. T, Feb. T, May P	....	5	5	0	4	0	1	5	0
Total		22	16	3	11	0	3	19	2
Per cent		100	100	14	69	0	19	86	12
Sum Total		207	220	43	115	15	43	149	62
Per cent		100	100	21	52	7	20	72	28

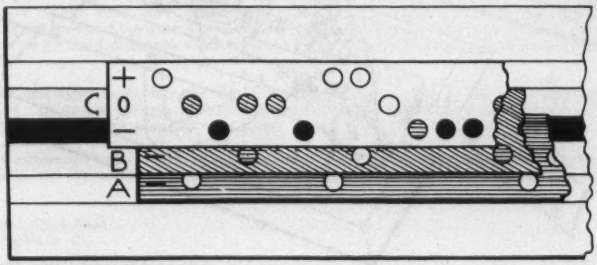


Fig. 3--Example of coincidence of three elements: (A) = excessive; (B) = normal; (C) = deficient, with time-lag of one unit

aligning of the three classes. Figure 2 shows a commercially available punch (A) whose lever (B) can be operated by means of a foot pedal and a string (not shown). A strip of paper, one inch wide, from the roll (C) slides along the trough (D). The roll can easily be sawed from any roll of paper such as graph-paper, adding-machine paper, etc. The strip of paper is moved by means of two rubber-hose-covered metal rollers (E) and (F), the latter being pressed against the former by a flat spring (G). The roller (E) is rotated by the ratchet-arrangement (H) operated by the lever (I) so as to feed one-third inch of paper with each lever-movement. All items (C) to (I) constitute one unit. On the underside of the trough two metal strips (K) with slots are fastened. Two metal plugs (L), which are attached to the base plate, go through these slots so that the whole trough-unit can be slid back and forth at right-angles to the trough. On each of the plugs a flat metal piece is pressed by means of a spring into one of three notches provided in each metal strip (K) 0.3 inch apart in order to confine the motion of the trough and provide for an easy alignment of the holes in one of the three classes mentioned above. It is evident that, instead of moving the paper back and forth, the punch could be moved in a similar fashion, and the trough be kept stationary.

The analysis of the punched strips of paper is facilitated by the white board (M) on which a black stripe, 5/16 inch wide, is painted. Two lines on either side of the black stripe serve as guides for lining up the paper-strips so that different classes can be superimposed over the black stripe. In this manner the coincidence of holes can readily be spotted and their number noted. For example, Figure 3 shows that when element A is excessive (+) and, simultaneously, B is normal (O) element C is, after a lag of one time-unit, deficient (-) in four cases within the section shown. In order to ascertain the significance of the number of occurrences of such coincidences, it must be shown that opposite, or at least different conditions for A and B, the same class of element C would produce significantly less coincidences.

As an example the tentative foreshadowing of the precipitation in June, 1944, at State College, Pennsylvania, is cited. As parameters, past data of the same station were used. Table 1 shows that in previous years during which various combinations of temperature- and precipitation-classes from January through May were the same as in 1944, precipitation in June was deficient in 72 per cent, normal in seven per cent, and excessive in 21 per cent of all cases, whereas the opposite conditions were connected with a precipitation in June which was deficient in only 28 per cent, normal in 20 per cent, and excessive in 52 per cent of all cases. The general frequency of the three classes of precipitation in June during 57 years of record is 35 per cent excessive, 17 per cent normal, and 47 per cent deficient, so that a possibility of deficient precipitation in June for 1944 at State College is greater than chance.

With this method of representation of climatic data on punched paper-strips, periodic recurrences of certain climatic features can be investigated by placing a template with two holes representing the tentative time-interval over the paper-strips containing the given climatic elements. Moving such a template over the paper-strips readily permits counting the number of recurrences of given climatic sequences. For instance, answers to questions such as the following can be found: How often is a month with a given class of climatic element followed, after a certain time-interval, by the same class of another element?

This method can naturally be applied to more than three classes if a wider strip of paper and a slightly modified punch is used. Also the counting of the holes can be done automatically with photoelectric counters; however, such a device increases the cost of the method out of proportion to the gain in speed of analysis.

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RADIATION AND CLOUDINESS

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The knowledge of the relation between climatological elements and factors is obviously basic, not only for a better physical understanding of the phenomena but also for the calculation of one variable from others which are often better and more completely known from observations.

This point of view is particularly valid for radiation-observations, the number of which is not only rather restricted on the surface of the Earth, but also the distribution of the places with such observations is disadvantageous. An overwhelming percentage of the stations are crowded in the highly cultivated countries.

Therefore, especially the radiation-elements give rise to such attempts as, for instance, the well-known ones of A. ÅNGSTROM [see 1 of "References" at end of paper] and H. H. KIMBALL [2]. The two authors investigate the relation between global radiation and relative duration of sunshine. KIMBALL discussed also the relation between global radiation and cloudiness.

In the present paper, the attempt is made to look for a simple relation between monthly radiation-quantities at normal incidence and climatological characteristics. Cloudiness and altitude of the Sun are two quantities which are known for many places and are, moreover, decisive factors for radiation-quantities. Because monthly radiation-quantities are considered, the Sun's altitude ($h_\odot$) is related to noon of the middle day of the month.

The simple assumption is made that the monthly quantities of radiation (Q_i, i from 1 to 12, denoting the number of the month) are proportional to the product of sin $h_\odot$ and the brightness of the sky (B), where B = (100 - C) if C is the mean monthly cloudiness expressed in per cent of the visible sky. Then the assumption reads $Q_i = k\, B_i \sin h_{\odot,i}$, where k is the coefficient of proportionality. This simple relation was applied to observations in three very different climates: (1) Monsoon climate of the middle latitudes; (2) Mediterranean climate; (3) climate of a high-level valley in the Alps.

(I) The observational material

The five publications from which the figures for the present investigation are taken contain the monthly radiation-quantities at normal incidence so that no further reduction is necessary.

The east coast of Asia is the monsoon coast par excellence. Radiation-quantities are available from Vladivostok, U.S.S.R., and from Tokyo, Japan. The observations at Vladivostok are edited by N. N. KALITIN in a publication not sufficiently distributed; the original values, therefore, are reproduced in Table 9 of this paper. The average monthly values of cloudiness are taken from the excellent study of A. SCHÖNROCK. Unfortunately the period of the radiation-observations is different from that of cloudiness. This circumstance could cause some error, the amount of which cannot be estimated quantitatively. However, the times of the phases of the annual course are of greater importance than the absolute quantities in this investigation. For the daily course of temperature, the present author showed that the phase-angles are scattered far less than the monthly averages of temperature itself. This result may be obvious because the average phase-angles are directly controlled by the Sun and by the physical properties of the ground. The temperature, however, is influenced by so many aperiodical and irregular factors that its scattering is by far greater. If this statement holds for a diurnal course, it may be the more valid for an annual course with its much slower periodical variations. So it can be assumed that the annual course of brightness of the sky, B, derived from the period 1880 to 1890 (SCHÖNROCK) is not essentially different from that of the period 1928 to 1933, the years of radiation-observation, as far as the phases are concerned. It may be remarked also that, in the case of the other four stations, the observational periods of radiation and cloudiness are not concurrent.

As may be seen from Table 9, there are some gaps in the series of Vladivostok and likely some misprints. An example is offered by the radiation-quantity of June, 1931, which is less than a third of the average of the four available months of June. It is unlikely that this exceedingly low value can be explained by forest-fires, by sandstorms, or something like that because maritime air-masses are prevalent in June. In any case, it was necessary to interpolate the gaps and to smooth carefully the resulting annual course.

The second station with monsoon climate is Tokyo. The relative values of the monthly radiation-quantities are likely all right. The absolute values, however, are obviously too low. Two reasons are conceivable for this fact, if a mistake in principle of the observational methods is disregarded: First, that there may be an exceedingly high local turbidity of the atmosphere; second, that the numbers published are not quantities at normal incidence but quantities received by a horizontal plane. This latter reason can be excluded as unlikely on the strength of a rather exact estimation. If the first assumption holds, a direct comparison with the Vladivostok series is not fully appropriate because, in a combination of the two series, that of Tokyo has a smaller weight. To avoid this unfitness, the monthly quantities of Tokyo were multiplied by the average ratio (Vladivostok/Tokyo) = 1.48; this reduction is, however, only applied when the two series are really combined, which will be done later on.

There is no special reason to discuss the series of Nice [7] and Ariana [8] as far as their statistical properties are concerned. Finally, it may be mentioned that the series for Arosa, Switzerland, originates from F. W. PAUL GÖTZ [9], the outstanding observer and analyst of geophysical phenomena. Thus, this series can be taken as a standard series.

Table 1--Data for Vladivostok, USSR
(47°07′ north, 131°54′ east, elevation 17 meters)

Month	Obs'd Q	B	h_e	k=(Q/B sin h_e)	Δk	Q calculated with $\bar{k}$	(O-C)	k_1 calculated, Fourier series*	Q calculated with fluct. k	(O-C)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
	a	pct	° ′							
Jan.	354	69	25 47	11.79	+0.96	324	+30	11.4	342	+12
Feb.	391	67	33 55	10.46	-0.24	361	+30	10.7	400	- 9
Mar.	386	56	44 48	9.78	-0.96	427	-41	10.0	395	- 9
Apr.	333	42	56 42	9.49	-1.34	379	-46	9.6	337	- 4
May	278	33	65 46	9.24	-1.35	325	-47	9.5	286	- 8
June	254	27	70 12	10.00	-0.83	274	-20	9.8	249	+ 5
July	251	25	68 24	10.80	-0.18	251	0	10.3	239	+12
Aug.	290	30	60 55	11.06	+0.32	283	+ 7	11.0	288	+ 2
Sep.	359	40	49 52	11.74	+0.76	330	+29	11.7	358	+ 1
Oct.	367	50	38 19	11.84	+0.90	335	+32	12.1	375	- 8
Nov.	312	57	28 22	11.52	+0.98	293	+19	12.2	331	-19
Dec.	318	64	23 36	12.41	+1.19	276	+42	11.9	305	+13
Mean	324	..	....	10.84	....	...	...	...	...	...

*$k = 10.84 + 1.36 \sin(x + 157.^\circ5) + 0.35 \sin(2x + 93.^\circ1) + 0.16 \sin(3x + 45.^\circ4)$

[a] Gram-calories per cm^2 per day.

Table 2--Data for Tokyo, Japan
(35°41′ north, 139°46′ east, elevation 6 meters)

Month	Obs'd Q	B	h_e	k=(Q/B sin h_e)	Δk	Q calculated with $\bar{k}$	(O-C)	k_1 calculated, Fourier series*	Q calculated with fluct. k	(O-C)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
	a	pct	° ′							
Jan.	221	55	33 13	7.34	-0.66	241	-20	7.49	225	- 4
Feb.	238	49	41 21	7.35	-0.65	259	-21	7.16	232	+ 6
Mar.	255	41	52 14	7.87	-0.13	259	- 4	7.63	247	+ 8
Apr.	260	34	64 08	8.50	+0.50	245	+15	8.86	271	-11
May	237	27	73 12	9.17	+1.17	207	+30	9.17	237	0
June	184	23	77 38	8.19	+0.19	180	+ 4	8.31	187	- 3
July	185	25	75 50	7.63	-0.37	194	- 9	7.89	191	- 6
Aug.	236	28	68 21	9.07	+1.07	208	+28	9.04	235	+ 1
Sep.	223	29	57 18	9.14	+1.14	195	+28	9.17	224	- 1
Oct.	192	35	45 45	7.66	-0.34	201	- 9	7.76	195	- 3
Nov.	194	48	35 48	6.91	-1.09	225	-31	6.63	186	+ 8
Dec.	207	56	31 02	7.17	-0.83	231	-24	6.89	199	+ 8
Mean	219	..	....	...	....	...	...	...	...	...

*$k = 8.00 + 0.77 \sin(x + 286.^\circ9) + 0.42 \sin(2x + 313.^\circ2) + 0.60 \sin(3x + 115.^\circ4)$

[a] Gram-calories per cm^2 per day.

(II) Annual course of observed totals of radiation at normal incidence

The annual course of the totals of radiation is given for the five stations mentioned in Column (2) of Tables 1 to 5. The numbers indicate the radiation-quantities of the middle day of the respective month in gram-calories per cm^2. (This notation is preferable to the true monthly totals because these are not comparable with each other in consequence of the unequal length of the months.)

The annual course at Vladivostok is noticeable indeed and shows a peculiarity which never has been pointed out to the author's best knowledge, although it is a striking characteristic of the mon-

Table 3--Data for Nice, France
(43°42′ north, 7°18′ east, elevation 200 meters)

Month (1)	Obs'd Q (2)	B (3)	$h_\odot$ (4)	k=(Q/B sin $h_\odot$) (5)	Δk (6)	Q calculated with $\bar{k}$ (7)	(O-C) (8)	k_1 calculated, Fourier series* (9)	Q calculated with fluct. k (10)	(O-C) (11)
	a	pct	° ′							
Jan.	368	58	25 12	14.90	+1.68	326	+42	15.05	372	- 4
Feb.	420	54	33 20	14.15	+0.93	392	+28	14.24	422	- 2
Mar.	477	49	44 13	13.96	+0.74	451	+26	13.64	465	+12
Apr.	538	52	56 07	12.46	-0.76	570	-32	12.81	553	-15
May	626	56	65 11	12.31	-0.91	671	-45	12.13	615	+11
June	665	60	69 37	11.82	-1.40	742	-77	11.77	663	+ 2
July	720	70	67 49	11.11	-2.11	854	-134	11.23	725	- 5
Aug.	697	75	60 20	10.70	-2.52	861	-164	10.68	698	- 1
Sep.	580	67	48 17	11.60	-1.62	660	-80	11.46	575	+ 5
Oct.	461	56	37 44	13.70	+0.48	445	+16	13.79	465	- 4
Nov.	367	50	27 47	15.75	+2.53	308	+59	15.83	368	- 1
Dec.	330	52	23 01	16.23	+3.01	268	+62	16.01	325	+ 5
Mean	521	..	....	13.22	....	...	...	....	...	...

*$k = 13.22 + 2.29 \sin(x + 101.^\circ1) + 0.83 \sin(2x + 185.^\circ9) + 0.34 \sin(3x + 277.^\circ9)$

[a] Gram-calories per cm^2 per day.

Table 4--Data for Ariana
(36°49′ north, 7° 57′ east, elevation 10 meters)

Month (1)	Obs'd Q (2)	B (3)	$h_\odot$ (4)	k=(Q/B sin $h_\odot$) (5)	Δk (6)	Q calculated with $\bar{k}$ (7)	(O-C) (8)	k_1 calculated, Fourier series* (9)	Q calculated with fluct. k (10)	(O-C) (11)
	a	pct	° ′							
Jan.	323	40	32 05	15.20	+3.55	247	+ .76	15.14	320	+ 3
Feb.	374	39	40 13	14.85	+3.20	294	+ .80	14.80	373	+ 1
Mar.	419	42	51 06	12.82	+1.17	381	+ .38	12.89	422	- 3
Apr.	478	49	63 00	10.95	-0.70	509	- .31	10.94	476	+ 2
May	543	56	72 04	10.19	-1.46	621	- .78	10.14	538	+ 5
June	637	66	76 30	9.93	-1.72	748	-1.11	9.94	638	- 1
July	709	78	74 42	9.42	-2.23	876	-1.67	9.50	714	- 5
Aug.	648	77	67 13	9.34	-2.31	827	-1.79	9.22	655	- 7
Sep.	501	62	56 10	9.73	-1.92	600	- .99	9.79	504	- 3
Oct.	399	52	44 37	10.92	-0.73	425	- .26	11.02	402	- 3
Nov.	331	46	34 40	12.65	+1.00	305	+ .26	12.44	325	+ 6
Dec.	289	42	29 54	13.80	+2.15	244	+ .45	13.98	293	- 4
Mean	471	..	....	11.65	....	...	....	....	...	...

*$k = 11.65 + 2.79 \sin(x + 85.^\circ2) + 0.67 \sin(2x + 87.^\circ9) + 0.27 \sin(3x + 8.^\circ1)$

[a] Gram-calories per cm^2 per day.

soon climate. We see in Column (2) of Table 1 a double-crested annual course with maxima in March and October, a secondary minimum in November and December, and an accentuated main minimum in June and July. This means that the smallest amounts of radiation are observed when the altitude of the Sun reaches its maximum.

The same is the case with the annual course of the totals of radiation at Tokyo (Table 2). There are two maxima, in April and August, a secondary minimum in October, and the main minimum in June. The two annual courses are not identical, but in any case the course at Tokyo verifies fully the interesting phenomenon.

Table 5--Data for Alpine climate, Arosa, Switzerland
(46°47′ north, 9°40′east, elevation 1860 meters)

Month	Obs'd Q	B	$h_\odot$	$k=(Q/B \sin h_\odot)$	Δk	Q calculated with $\bar{k}$	(O-C)	k_1 calculated, Fourier series*	Q calculated with fluct. k	(O-C)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
	a	pct	° ′							
Jan.	284	53	22 06	14.24	-0.28	289	- 5	14.66	293	- 9
Feb.	398	51	30 24	15.42	+0.90	379	+19	15.16	392	+ 6
Mar.	447	44	41 00	15.48	+0.96	419	+28	15.80	457	-10
Apr.	459	37	52 54	15.55	+1.03	428	+31	14.90	440	+19
May	428	37	62 00	13.10	-1.42	473	-45	13.37	437	- 9
June	452	36	66 30	13.69	-0.83	479	-27	13.41	442	+10
July	522	41	64 48	14.07	-0.45	538	-16	14.62	542	-20
Aug.	574	46	57 24	14.79	+0.27	563	+11	14.78	571	+ 3
Sep.	492	48	46 18	14.18	-0.34	503	-11	13.92	482	+10
Oct.	387	49	34 48	13.84	-0.68	406	-19	13.90	389	- 2
Nov.	324	51	24 48	15.15	+0.63	310	+14	14.77	317	+ 7
Dec.	258	51	20 00	14.79	+0.27	252	+ 7	14.95	261	- 3
Mean	419	..	....	14.52	....	...	...	....	...	...

$$*k = 14.52 + 0.57 \sin(x + 76.^\circ2) + 0.47 \sin(2x + 345.^\circ8) + 0.64 \sin(3x + 235.^\circ6)$$

[a] Gram-calories per cm^2 per day.

Table 6--Data for Monsoon climate, [(Vladivostok + 1.48 Tokyo)/2]
(39°24′ north)

Month	Obs'd Q	B	$h_\odot$	$k=(Q/B \sin h_\odot)$	Δk	Q calculated with $\bar{k}$	(O-C)	k_1 calculated, Fourier series*	Q calculated from fluct. k	(O-C)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
	a	pct	° ′							
Jan.	340	62	29 30	11.14	-0.11	343	- 3	11.23	342	- 2
Feb.	372	58	37 38	10.50	-0.75	398	-26	10.59	375	- 3
Mar.	382	48	48 31	10.62	-0.63	405	-23	10.42	374	+ 8
Apr.	359	38	60 25	10.86	-0.39	371	-12	11.04	363	- 4
May	314	30	69 29	11.33	+0.08	312	+ 2	11.28	313	+ 1
June	263	25	73 55	10.96	-0.29	270	- 7	10.88	262	+ 1
July	262	25	72 07	11.01	-0.24	268	- 6	11.12	264	- 2
Aug.	320	29	64 38	12.21	+0.96	294	+26	12.19	320	0
Sep.	344	34	53 35	12.57	+1.32	308	+36	12.59	343	+ 1
Oct.	326	42	42 02	11.59	+0.34	316	+10	11.62	326	0
Nov.	300	52	32 05	10.86	-0.39	310	-10	10.94	301	- 1
Dec.	312	60	27 19	11.33	+0.08	310	+ 2	11.18	308	+ 4
Mean	324	..	....	11.25	....	...	...	....	...	...

$$*k = 11.25 + 0.63 \sin(x + 216.^\circ3) + 0.22 \sin(2x + 338.^\circ3) + 0.48 \sin(3x + 117.^\circ9)$$

[a] Gram-calories per cm^2 per day.

The correlation between the two series is evidently so significant that one may combine the two courses to an average course. This has been done in Column (2) of Table 6. For reasons mentioned earlier, the numbers for Tokyo are multiplied by 1.48, in order to give them the same weight as those for Vladivostok.

As it is seen from the numerical values [Col. (2), Table 6] and especially clearly from Figure 1, the combination of the two series results in a smooth curve which represents the new phenomenon in an excellent way. The maxima occur in March and September, the secondary minimum in November, and the main minimum about the first part of July.

For a comparison, the necessity of which becomes evident in the following section, two places with radiation-records are chosen with a typical Mediterranean climate, namely, Nice (France) and Ariana (Algiers). The trend of the annual course in this climate is quite different from that in the monsoon climate and is much simpler. It is the type which would be generally expected, that is, a maximum in the last third of July and a minimum in the middle of December. The curve is, however, characterized by an exceedingly steep ascent to a very sharp peak in July and an even still more rapid drop to the accentuated minimum in December. Thus the trend of the annual course in the monsoon climate contrasts strongly with that in the Mediterranean climate.

Now the behavior of the annual curve in the Alpine climate of a rather elevated place shows common features with the Mediterranean curve as well as with the monsoon curve. There we find the simple annual course with one maximum and one minimum, on the one hand. But, on the other hand, the transition from one extreme to the other is not so rapid and, moreover, a depression is to be seen in the values for May through July. Also the annual range lies between that of the other two types, as it is clear from the last line of Table 8. The unequal latitudes are not of importance. On the contrary, if the ranges of the three series are reduced to equal latitude, the new percentages read 4.9, 10.7, and 8.8, and show the better that the range at the Alpine station is between that of the monsoon climate and the Mediterranean climate.

The three annual courses of the totals of radiation are easily explained by the conditions of cloudiness, characteristic for each climate.

Summer rains accompanied by great amounts of cloudiness are typical for a monsoon coast such as the east coast of Asia. According to Column (3) of Table 6, the brightness of the sky reaches its minimum in June and July. In winter the maximum of brightness occurs with the minimum of clouds. Now the insolation is increased with increasing altitudes of the Sun. However, cloudiness is increased too and over-compensates the effect of the further rising altitude of the Sun. Thus the radiation-curve (monthly totals at normal incidence) is strongly depressed from March through September, and cloudiness is so effective that the main minimum of the year occurs at the end of June or in the very first days of July (Fig. 1) at the greatest altitude of the Sun.

The annual course of radiation in the Mediterranean climate is easily understood by the fact that this climate has the rainy period in winter with relatively great amounts of cloudiness. Conversely the brightness of the sky has its minimum in winter [Col. (3), Table 7] and a sharp maximum in summer. Thus the effect of the variations of the altitude of the Sun and of the degree of brightness strengthen one another.

The annual course at Arosa (Alpine type) is explained with the great cloudiness in April, May, and June. The depression in the radiation-curve is fully equivalent to the summer depression in the monsoon climate but is less intensive so that only a secondary minimum is caused [Cols. (2) and (3), Table 5, and Fig. 3].

(III) The equation $Q_i = k_i B_i \sin h_{\odot,i}$

Thus the annual courses of the totals of radiation are given for three very different climates in regions 11,000 km apart. The problem is whether or not it is possible to represent these different courses by one and the same given form of an analytic equation.

This is the main attempt made in the present investigation. The simple assumption which leads to the equation $Q_i = k_i B_i \sin h_{\odot,i}$ is outlined in the introduction. The basic values, taken from the records, Q_i, B_i, and $h_{\odot,i}$, are given in Columns (2), (3), and (4) of Tables 1 to 7. From these series the coefficient k and the deviations, Δk, are easily calculated [Cols. (5) and (6)].

Perhaps, with the exception of Tokyo and Arosa, the coefficient k shows a clear annual course. The yearly means are noted at the end of Column (5). The annual course is given by the Fourier series at the bottom of Tables 1 to 7. The annual courses differ, however, from one another by their ranges as follows: Vladivostok, 16 per cent; Tokyo, 18 per cent; Nice, 38 per cent; Ariana, 50 per cent; Arosa, 17 per cent. The percentages mean the differences, maximum minus minimum of k, in per cent of the arithmetical mean.

The contrast between the climatic conditions becomes perhaps still clearer by giving the relative amplitudes of the first term of the series for the two combined groups (Tables 6 and 7) and for Arosa, namely: Monsoon climate, 5.6 per cent; Mediterranean climate, 20.0 per cent; Alpine climate, 3.9 per cent. It is surprising that the radiation-climate of the east coast of Asia at

Table 7--Data for Mediterranean climate, [(Nice + Ariana)/2] (40°16′ north)

Month	Obs'd Q	B	$h_\odot$	k=(Q/B sin $h_\odot$)	Δk	Q calculated with $\bar{k}$	(O-C)	k_1 calculated, Fourier series*	Q calculated with fluct. k	(O-C)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
	a	pct	° ′							
Jan.	346	49	28 38	14.73	+2.39	289	+ 57	14.83	348	+ 1
Feb.	397	46	36 46	14.42	+2.08	338	+ 59	14.42	396	+ 1
Mar.	448	45	47 39	13.47	+1.13	410	+ 38	13.34	443	+ 5
Apr.	508	50	59 33	11.79	-0.55	530	- 22	11.98	517	- 9
May	585	56	68 37	11.22	-1.12	642	- 57	11.12	597	+ 6
June	651	63	73 03	10.80	-1.54	742	- 91	10.77	651	0
July	714	74	71 15	10.19	-2.15	862	-148	10.27	722	- 8
Aug.	672	76	63 46	9.86	-2.48	839	-227	9.84	671	+ 1
Sep.	540	64	52 43	10.60	-1.74	626	- 86	10.50	534	+ 6
Oct.	431	54	41 10	12.13	-0.21	437	- 6	12.28	437	- 6
Nov.	349	48	31 13	14.03	+1.69	306	+ 43	13.98	349	0
Dec.	310	47	26 27	14.81	+2.47	257	+ 53	14.75	309	+ 1
Mean	496	..	....	12.34	....	...	....	....	...	...

*$k = 12.34 + 2.47 \sin(x + 90.0°) + 0.42 \sin(2x + 149°.4) + 0.24 \sin(3x + 308°.0)$

[a] Gram-calories per cm^2 per day

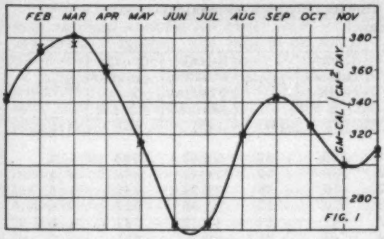
Table 8--Annual course of monthly totals in per cent

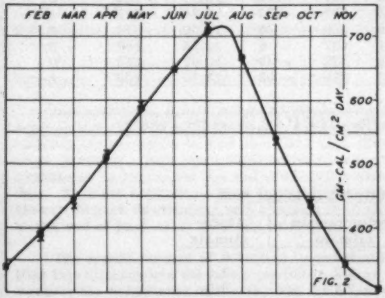
Month	Monsoon climate	Mediterranean climate	Alpine climate
Jan.	8.7	5.8	5.7
Feb.	9.6	6.7	7.9
Mar.	9.8[a]	7.5	8.9
Apr.	9.2	8.5	9.1
May	8.1	9.8	8.5
June	6.8	10.9	9.0
July	6.7[b]	12.1[a]	10.4
Aug.	8.2	11.3	11.5[a]
Sep.	8.8	9.1	9.8
Oct.	8.4	7.2	7.7
Nov.	7.7	5.9	6.4
Dec.	8.0	5.2[b]	4.1[b]
Range	3.1	6.9	6.4

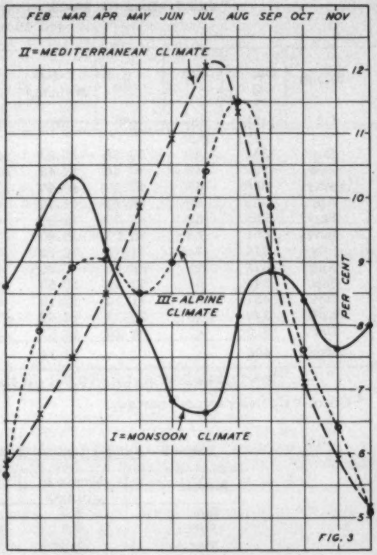
[a] Maximum. [b] Minimum.

Table 9--Monthly totals of radiation (in gram-calories per cm^2) at normal incidence at Vladivostok, USSR

Month	Year				
	1928	1929	1930	1931	1933
Jan.	10,796	11,853	12,833	8,939	11,530
Feb.	12,118	10,816	8,748	11,813	11,809
Mar.	13,527	13,363	9,744	13,035	14,095
Apr.	.....	10,401	9,313	8,097	11,412
May	7,258	.....	9,805	7,005	9,214
June	7,534	.....	8,767	2,142	11,266
July	.....	.....	6,622	6,360	10,511
Aug.	7,650	.....	7,898	8,097	7,620
Sep.	11,601	14,267	13,606	9,026	.....
Oct.	11,135	10,488	12,312	12,698	.....
Nov.	7,513	11,713	9,274	8,966	.....
Dec.	11,019	6,860	9,719	9,637	.....







Figs. 1-3--(1) Average totals of observed (•) and calculated (×) radiation for [(Vladivostok + 1.48 Tokyo)/2] (2) Average totals of observed (•) and calculated (×) radiation for [(Nice + Ariana)/2] (3) Monthly totals of radiation in per cent of total of year for monsoon, Mediterranean, and Alpine climates

sea-level and a valley in the Alpine high mountains at 1860 meters show common features. But there can be no doubt if the aforementioned numbers are considered. Roughly speaking, not only does the annual course of cloudiness show monsoon-like features in the higher levels of the high mountains in middle latitudes, but also some similarity can be concluded also from another point of view.

An examination of the Fourier series for k results in the following statements: (a) The series of k in the monsoon climate is not convergent; (b) that in the Mediterranean climate is decidedly convergent; and (c) that in the Alpine climate is not convergent. (Here it must be pointed out that k for Vladivostok is represented by a convergent series, which, however, in spite of the calculation of three terms, shows rather great residuals. If the critical remarks about gaps, misprints, etc., are considered, the reader can understand that greater weight is laid on the combination of the observations of Vladivostok and Tokyo. Also the necessary smoothing of the series can contribute to the convergence.)

Summarizing we must say that the coefficient k shows an annual course in all the three climates mentioned. But in the monsoon climate and in the Alpine climate the relative amplitude of the annual course is small in comparison with that in the Mediterranean climate. The following conclusion is also strengthened by considering the conditions of convergence of the Fourier series which represent the annual courses.

From these considerations the monthly totals of radiation can be represented for the monsoon and for the Alpine climate in a very simple manner. The factor k_i in the formula $Q_i = k_i B_i \sin h_{\odot,i}$ can be taken constant and equal to $\bar{k}$, the arithmetical mean of the monthly values of k. Thus the

Q_i calculated with $\bar{k}$ appear in Column (7) of Tables 1 to 7. Column (8) contains the residuals [Col. (2) minus Col. (7), that is, observed minus calculated].

For brevity we restrict the discussion to Tables 5, 6, and 7 or the Alpine climate, the monsoon climate, and the Mediterranean climate. Calculating the average residual, we get the following results:

Monsoon climate--Average residual of the monthly radiation-quantity = 4.3 per cent.
Alpine climate--Average residual of the monthly radiation-quantity = 4.6 per cent.
Mediterranean climate--Average residual of the monthly radiation-quantity = 15 per cent.

This result means that the radiation-totals can be represented in monsoon climate, European Alpine climate, and climates with similar properties in a very simple manner for which two examples are here calculated: For monsoon climate, $Q_i = 11.2\ B_i \sin h_{\odot,i}$; for Alpine climate, $Q = 14.5\ B_i \sin h_{\odot,i}$. These formulas yield an average error of about four per cent and a maximal error of about ten per cent, in both cases.

It is rather likely, from what is said later on, that k increases with the height of the respective place; moreover, there is a certain indication, which seems to be valuable, that k is not subject to too great variations. The values of k calculated in this paper are: Vladivostok, 11; Tokyo (reduced), 12; Nice, 13; Ariana, 12. So long as places in lower levels are considered, the coefficient k varies surprisingly little. Therefore, it does not appear unlikely that further investigations in this field could show a constant coefficient k as valid for considerable portions of the surface of the Earth.

Column (9) of the Tables contains the coefficient k calculated from the Fourier series given at the bottom of each Table. In Column (10) appear the radiation-quantities calculated with the values of k_i in Column (9) and the residuals in Column (11).

These last three series are also given in Tables 1, 2, 5, and 6. Their meaning is but to show what accuracy one gets when the annual course of k is considered. The average errors are below three per cent and the maximal individual error reaches six per cent in the case of a single month. Therefore, it is quite possible to represent the monthly totals of radiation by means of the aforementioned equation.

It is another matter with the conditions in the Mediterranean climate (Tables 3, 4, and 7). Here the annual variation of k is rather important. Therefore, the annual course of k must also be considered in the equation for the values of Q_i.

Previously it was stated that the Fourier series for k are convergent for the Mediterranean climate. If a_1 denotes the amplitude of the first term of Fourier's series, a_2 the amplitude of the second term, and so on, the ratios (a_2/a_1) and (a_3/a_1) for Nice, for Ariana, and for the combined Mediterranean climate are: 0.36 and 0.15; 0.24 and 0.10; and 0.17 and 0.10. This means that the convergence of the series is so pronounced that only the first term must be considered in a first approximation. Then we get the following equation for the Mediterranean climate:

$$Q_i = [12.3 + 2.5 \sin (x + 90^\circ 0)]\ B_i \sin h_{\odot,i}$$

Perhaps it would suffice to leave out the decimal figures.

The phase-angle of the first and decisive term of k is 101° at Nice and 85° at Ariana. The difference is only 16° or about 16 days. (Nice and Ariana are 500 miles apart.) So it is not at all excluded that also the phase-angle shows only small variations over great regions of the Earth.

(IV) Nature of the coefficient k

At first glance the coefficient k could be nothing but a statistical factor. This impression is changed if the annual course of k in the Mediterranean climate is more closely examined. Corresponding with the phase-angle of 90° (Table 7) the maximum of k occurs in the middle of January, the minimum in middle of July. This course is nearly parallel to that of cloudiness. It is hard to believe that this is a mere chance. On the other hand, cloudiness and altitude of the Sun may be fully considered in the equation by means of the product $B_i \sin h_{\odot,i}$. The variations of k, therefore, must be an effect of the third factor decisive for the intensity of radiation, which is not regarded in the formula, that is, the turbidity of the air. In winter of the Mediterranean climate, in

the rainy season the relative humidity reaches its maximum, but the vapor-pressure or the absolute humidity are at their minimum because of the low temperature. In summer the opposite conditions hold. Low to very low relative humidities occur, but the vapor-pressure reaches its maximum because of the high temperatures. An example, taken from the observations in lower Egypt [10], may be illustrative: For Qasr el Gebali (29°.3 north, 30°.6 east) the relative humidity is 74 per cent and the vapor-pressure is 9.8 mb in winter, and 55 per cent and 20.0 mb in summer. So far as the water-vapor content is concerned, the turbidity is greater in summer than in winter. In winter, the rainy period, the frequent condensations precipitate the pollutions and make the atmosphere rainy period--the frequent condensations precipitate the pollutions and make the atmosphere clean. Summer, however, is the season of dust-storms and smaller sandstorms which lift enormous masses of material and distribute it to high altitudes. Because of the lack of rain in summer, the dust remains suspended for a long time in the atmosphere and accumulates. Thus the turbidity has its maximum in summer and its minimum in winter. That is again opposite to the course of the coefficient k. But the counterpart of the turbidity, the transparency of the atmosphere, shows a nearly identical annual course to that presented by the coefficient k. It may be rather probable, therefore, that the coefficient k represents a sort of transmission-coefficient. These conclusions may be very probable but they lack quantitative evidence.

It is fortunate that GÖTZ published in his "Strahlungsklima von Arosa" not only turbidity-factors (p. 30) but also transmission-coefficients (p. 33) for Arosa although not for a period identical with that of the radiation-quantities used here. Thus the correlation could be calculated between the coefficients k_i and the turbidity factors (T_i) on the one hand and with the transmission-coefficients (C_i) on the other hand. The results are: $r(k_i, T_i) = -0.555 \pm 0.135$. The decisive relation between the correlation-coefficient r and the probable error is only 4.0. Nevertheless, it is noticeable that the correlation is a negative one. The course of k and that of the turbidity-factor are opposite to one another. Furthermore, $r(k_i, C_i) = +0.662 \pm 0.109$. There is no doubt that a positive correlation exists between k and the transmission-coefficient. The correlation-coefficient r is 6.1 times greater than the probable error. The trustworthiness of this correlation is also strengthened by the negative sign of the correlation $r(k_i, T_i)$. Thus the investigation shows that the factor k is a sort of a general transmission-coefficient. This is the physical interpretation of k, which represents the third factor influencing the incoming radiation-quantities by means of the transparency of the atmosphere.

Finally, it may be remarked that the amplitude of the first term of k_i for Ariana is 2.8 and for Nice it is 2.3. On the one hand, the variation is not so great in spite of the considerable distance between the two places; this circumstance would be of great importance if it would hold for further investigations in reaching a generalization of the equation. On the other hand, the calculated amplitudes fit the physical explanation well. Ariana with the somewhat greater amplitude is located at the border of the Sahara Desert. The variation of dust-content is there obviously greater than in Nice on the opposite side of the Mediterranean Sea.

The coefficient k is not so variable in the monsoon climate in the course of the year and can be taken as constant if only a rough approximation is needed. It is significant that the same kind of inference is applicable for explaining the quasi-constancy of k on the coast of east Asia as was used to explain the rather strong annual course of k in the Mediterranean climate. In the latter, water-vapor content and dust-content run parallel to one another in the course of the year so that an effective variation of the transparency of the atmosphere is caused. On the east coast of Asia the vapor-pressure is very low in winter because of the low temperatures; the prevailing wind-direction is, however, from the interior of the Continent and the winds transport much dust originating from deserts and steppes. The result is a dry air polluted with much dust, showing more or less medium turbidity. In summer the monsoon rain cleans up the atmosphere and pure oceanic air-masses blow inland. But at relatively high temperatures the air is nearly saturated with water-vapor. The very humid, even if pure, atmosphere shows probably a medium transparency again. Thus it appears not unlikely that the transparency, and with it the coefficient k, is subject only to small and irregular variations, so that the quasi-constancy of k in the monsoon climate is explained on the basis of the same principles as the periodical fluctuations in the Mediterranean climate.

In the Alpine valley, represented by Arosa, quasi-constancy of k is also observed, perhaps in its best development. Here the method of explaining holds better because the variations of transparency within the year are quantitatively known. The transmission-coefficients, given by F. LINKE exhibit also very small variations with an amplitude of 2.7 per cent of the annual average.

Thus it seems to be possible to calculate monthly totals of radiation at normal incidence from cloudiness and altitude of the Sun by means of a simple analytical equation. The essential point is

that the coefficient k is seemingly not too variable from region to region and, even in those climates in which k is subject to periodical annual variation, amplitude and phase-angle vary little and smoothly. Therefore, it can be hoped that further investigations in this direction could offer means to calculate radiation-quantities for the many places on the Earth where cloudiness is recorded, based on the aid of the network with its too wide meshes of radiation-observatories. Thus this investigation will perhaps contribute to our knowledge of the incoming radiation-current.

Summary

(1) The annual course of observed monthly totals of radiation at normal incidence is discussed for the monsoon climate, the Mediterranean climate, and the European Alpine climate. The last two correspond to the general expectation with a minimum of radiation in winter and a maximum in summer. The annual course in the monsoon climate, however, offers a paradoxical annual course with the main minimum in summer. The physical explanation is given.

(2) The attempt has been made to represent the monthly totals (Q_i) by the equation $Q_i = k_i B_i \sin h_{\odot,i}$, where $B_i = (100 - C_i)$ and C_i is the cloudiness in per cent, and $h_{\odot,i}$ denotes the altitude of the Sun at noon of the middle day of the respective month ($i = 1$ to 12). The equation leads to good results in all three very different climates.

(3) It is shown in different ways that k_i is a relative measure of the transparency of the atmosphere; k_i is quasi-constant in the monsoon and in the Alpine climate and has an annual course in the Mediterranean climate. The different behavior of k is explained by the average atmospheric processes.

(4) Finally, it is shown that seemingly k itself is not subject to great variations so that an average k could be valid for great regions of the surface of the Earth. In climates in which k fluctuates periodically, the phase-angle and the amplitude of the first term vary neither much nor quickly (in consequence of a pronounced convergence of the series, the second and higher terms can be neglected).

Thus the method enables perhaps the calculation of totals of radiation for numerous places (from which records of cloudiness exist) checked by records of the sparse network of radiation-observatories.

The investigation is therefore a contribution to a better knowledge of the incoming radiation-current.

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ON THE RELATION BETWEEN MEAN CLOUDINESS AND THE NUMBER OF CLEAR AND CLOUDY DAYS IN THE UNITED STATES

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The peculiar frequency-distribution of values of cloudiness in the latitudes which are under the influence of polar-front cyclonic circulation has been a subject of discussion in the meteorological literature. As is well known, the frequency of cloudiness in these regions has two modes, one at 0/10, the other at 10/10. This leads to the uncommon U-shaped frequency-curve. The problem arises, of course, if under the circumstances values of mean cloudiness have any meaning or usefulness beyond offering an opportunity to compare the cloudiness at various places by using one figure only. Hence the question is: Does the mean cloudiness permit one to make any statements about the frequency of clear and cloudy sky at a given place?

The reverse question has been dealt with on various occasions, namely, whether the mean cloudiness can be satisfactorily obtained if the frequency of the two ends of the distribution is known. In those cases the number of clear and cloudy days during a given month is known and the mean cloudiness is desired. It was first found by MANTEL and substantiated by others that there exists a linear relation between the mean cloudiness and the difference of the numbers of clear and cloudy days. The equation has the form

$$N = a + b\,[(d - c)/n] \qquad (1)$$

with the following notation: N = Mean cloudiness; a,b = Constants; d = Dull (cloudy) days; c = Clear days; and n = Number of days in period. This general relation holds as a good approximation even though the definition of clear and cloudy days may vary somewhat in different networks of stations.

The value of the constants a and b has been established for various regions, as shown in Table 1.

Table 1--Numerical value of constants in equation (1) in various regions

Region	a	b	Source
Northern Germany	52	49	Kremser
Switzerland	51	49	Kremser
Norway	51	51	Kremser
Russia	50.5	52	Kremser
Poland	51	50	Gorczynski and Wierzbicka
Palermo	48	40	Kremser
Havana (October-March)	47	49	Drapzynski
Havana (April-September)	47	54	Drapzynski
Havana (Year)	47	51	Drapzynski

The fact that the relation between mean cloudiness and the difference of clear and cloudy days exists suggested that each of these quantities separately might also show a simple relation to the mean cloudiness. This hypothesis was tested with data from 110 stations in the United States. In order to see if any marked seasonal variation is present the values for January, April, July, and October were used separately. If the numbers of clear days and of cloudy days are plotted against the mean cloudiness, within certain limits the data arrange themselves rather well on straight lines. This answers the initial question in the affirmative and means that data for mean cloudiness can be interpreted in terms of the modes of the cloudiness-distribution. It also implies that equation (1) can be obtained as difference of the equations established for clear and cloudy days separately. These equations (2) for the above-mentioned four months at the 110 stations in the United States are given in Table 2.

Table 2--Equations for the number of clear and cloudy days as function of the mean cloudiness in the United States

Month	Cloudy days	Clear days
January	$d_1 = 0.35\,N_1 - 7.3$	$c_1 = -\,0.32\,N_1 + 27.8$
April	$d_4 = 0.31\,N_4 - 6.3$	$c_4 = -\,0.27\,N_4 + 24.8$
July	$d_7 = 0.27\,N_7 - 4.4$	$c_7 = -\,0.42\,N_7 + 31.2$
October	$d_{10} = 0.33\,N_{10} - 6.3$	$c_{10} = -\,0.33\,N_{10} + 29.0$

These equations hold well for values of mean cloudiness between about 30 and 75 per cent. The deviations from these lines are particularly pronounced for the cloudy days correlated to mean cloudiness below 30 per cent and for the clear days correlated to mean cloudiness above 75 per cent. From a practical point of view this discrepancy has relatively little significance because with a cloudiness under 30 per cent the number of cloudy days has gone below four per month, while for cloudiness over 75 per cent the clear days are less than four per month. The curves from these points drop off more slowly toward zero than the straight-line relationship would indicate. It is interesting to note that in case of the cloudy days the equations for January, April, and October are very nearly alike. Even for July the slope of the line is not much different from those for the other seasons. For the clear days the annual variation shown by the equations is much more pronounced. Especially in July, the slope of the line is rather different from that of the other months. The line drops off toward zero with increasing cloudiness at a more rapid rate than in the other months. This indicates undoubtedly the influence of convective cloudiness which is apt to reduce the number of clear days in summer.

The values for the constants a and b in equation (1), if calculated by the equations in Table 2 and directly from the difference of the clear and cloudy days for data from the United States, are given in Table 3.

Table 3--Values of constants in equations (1) and (2) for United States

Month	Calculated from (d - c)		Calculated from equations (2)	
	a	b	a	b
January	52.8	46.6	52.1	46.5
April	52.1	50.2	52.5	50.9
July	54.2	47.1	55.0	49.6
October	53.0	46.6	52.0	46.6

Considering the fact that the lines representing (d - c) and the clear and cloudy days separately were obtained graphically, the agreement is as close as might reasonably be expected.

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USE OF EQUIVALENT-POTENTIAL TEMPERATURES IN THE ANALYSIS OF DEPENDENT CLIMATE

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Introduction--Saint Louis, Missouri, is not located in a primary air-mass-source region and the air-masses which are found over the city have migrated from other provinces. Such migrating air-masses contribute much to the day-to-day variability of the meteorological elements at Saint Louis, so that in the climatology of the city air-masses are recognized as important climatic controls. Hence it would seem that a clearer understanding of local variability can be derived from discussions of the air-mass climate from manifold viewpoints.

Table 1--Thirty-year normal values of daily mean surface equivalent-potential temperature at Saint Louis, Missouri (° absolute)

Day	Month											
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
1	279.3	279.7	284.4	294.0	307.1	321.9	332.9	335.6	328.0	313.3	296.9	285.0
2	279.3	279.8	284.7	294.4	307.5	322.4	333.2	335.6	327.5	312.7	296.4	284.8
3	279.2	279.9	284.9	294.8	308.0	322.8	333.4	335.5	327.1	312.2	295.9	284.5
4	279.1	280.0	285.2	295.1	308.5	323.3	333.6	335.4	326.7	311.7	295.5	284.2
5	279.1	280.1	285.4	295.5	309.0	323.7	333.9	335.2	326.3	311.1	295.0	284.0
6	279.1	280.3	285.7	295.9	309.5	324.1	334.0	335.1	325.8	310.5	294.5	283.7
7	279.1	280.4	286.0	296.3	310.0	324.6	334.2	334.9	325.4	310.0	294.1	283.4
8	279.1	280.5	286.2	296.7	310.5	325.0	334.3	334.8	324.9	309.4	293.6	283.2
9	279.1	280.7	286.5	297.1	311.0	325.4	334.5	334.7	324.5	308.9	293.1	282.9
10	279.1	280.8	286.8	297.6	311.5	325.8	334.6	334.5	324.0	308.3	292.7	282.7
11	279.1	281.0	287.1	298.0	312.0	326.2	334.7	334.3	323.6	307.7	292.3	282.4
12	279.1	281.1	287.4	298.4	312.4	326.7	334.9	334.1	323.1	307.2	291.9	282.2
13	279.0	281.3	287.7	298.8	312.9	327.1	335.0	333.9	322.6	306.7	291.5	282.0
14	279.0	281.5	287.9	299.3	313.4	327.5	335.1	333.7	322.2	306.1	291.1	281.7
15	278.9	281.6	288.2	299.7	313.9	327.9	335.2	333.5	321.7	305.6	290.6	281.5
16	278.9	281.8	288.5	300.2	314.3	328.2	335.3	333.2	321.2	305.1	290.2	281.4
17	278.9	282.0	288.8	300.6	314.8	328.6	335.5	333.0	320.7	304.6	289.8	281.2
18	278.8	282.2	289.1	301.0	315.3	328.9	335.6	332.7	320.2	304.0	289.5	281.1
19	278.9	282.4	289.4	301.5	315.8	329.3	335.7	332.4	319.7	303.5	289.1	280.9
20	278.9	282.6	289.8	302.0	316.3	329.7	335.8	332.1	319.1	303.0	288.7	280.7
21	278.9	282.7	290.1	302.4	316.8	330.0	335.8	331.8	318.6	302.5	288.4	280.6
22	279.0	282.9	290.4	302.9	317.3	330.3	335.8	331.5	318.1	302.0	288.0	280.5
23	279.0	283.1	290.8	303.3	317.7	330.6	335.8	331.2	317.5	301.5	287.6	280.3
24	279.1	283.3	291.1	303.8	318.2	330.9	335.9	330.9	317.0	301.0	287.3	280.2
25	279.1	283.5	291.5	304.3	318.7	331.2	335.9	330.5	316.5	300.4	286.9	280.0
26	279.2	283.7	291.8	304.7	319.1	331.6	335.9	330.2	316.0	299.7	286.6	279.9
27	279.3	284.0	292.2	305.2	319.6	331.9	335.9	329.8	315.4	299.4	286.3	279.8
28	279.4	284.2	292.6	305.6	320.1	332.2	335.8	329.5	314.9	298.9	286.0	279.6
29	279.5		292.9	306.1	320.6	332.4	335.8	329.1	314.4	298.4	285.6	279.5
30	279.6		293.3	306.6	321.0	332.7	335.7	328.7	313.8	297.9	285.3	279.5
31	279.6		293.6		321.5		335.7	328.4		297.4		279.4

In recent years air-mass climatology has answered the question of regional air-mass predominance by tabulating the frequency of occurrence of air-mass types for a definite time-period [see 1 of "References" at end of paper]. Some such technique is necessary since the corollaries of the polar-front theory exclude the general existence of real "mean air-mass types" and the ordinary climatological ideas of average, mean, and normal cannot be directly applied to the air-mass. Studies of frequency-types are based on the synoptic identification of individual air-masses. From the viewpoint of interpretation, climatic studies are needed which show how the air-masses are related to the climatic elements.

Equivalent-potential temperature (θ_E), as defined by a pseudoadiabatic process [2], is an element of air-mass analysis. The possibilities of this quantity as a surface climatic tool have not been widely explored. Its place in analytical climatology has been questioned, for it is not a simple climatic element. It is a complex quantity. However, it possesses the characteristics of an integrating factor. For this reason it may be of assistance in the difficult task of climatic synthesis.

Annual march of mean surface θ_E at Saint Louis, Missouri--In the present preliminary study, which was intended to lay a basis for future work, the equivalent-potential temperatures caiculated from the observations taken at 07^h and 19^h, Central Standard Time (CST) at the Saint Louis University Observatory from 1913 to 1942 were examined for possible climatic uses.

At first the annual march of daily mean surface equivalent-potential temperature was determined from the 30 years of observational data. The daily means were computed by taking the average of the values at 07^h and 19^h of θ_E which were determined from the surface observations of temperature, pressure, and dew-point. The daily values of mean θ_E, derived from the above-mentioned data as a smoothed harmonic function, are given in Table 1. A Fourier analysis of the type applied to mean air-temperatures by MARVIN [3] was used for the smoothing.

This smoothed normal curve of daily mean θ_E at Saint Louis is quite similar to the annual mean temperature-curve. It differs, however, in amplitude- and phase-relations. The extremes of this smoothed annual curve convey some interesting information relative to the seasonal differences of the surface-air potentialities at Saint Louis. The annual minimum value of mean θ_E is 278.°8 A, which occurs on January 18; the annual maximum of mean θ_E is 335.°9 A, which occurs on July 25. The annual range of the mean is therefore 57.°1 C.

Equivalent-potential temperature-difference--The seasonal contrast in surface-air properties is brought out even more strikingly if the data are given in the form of the equivalent-potential

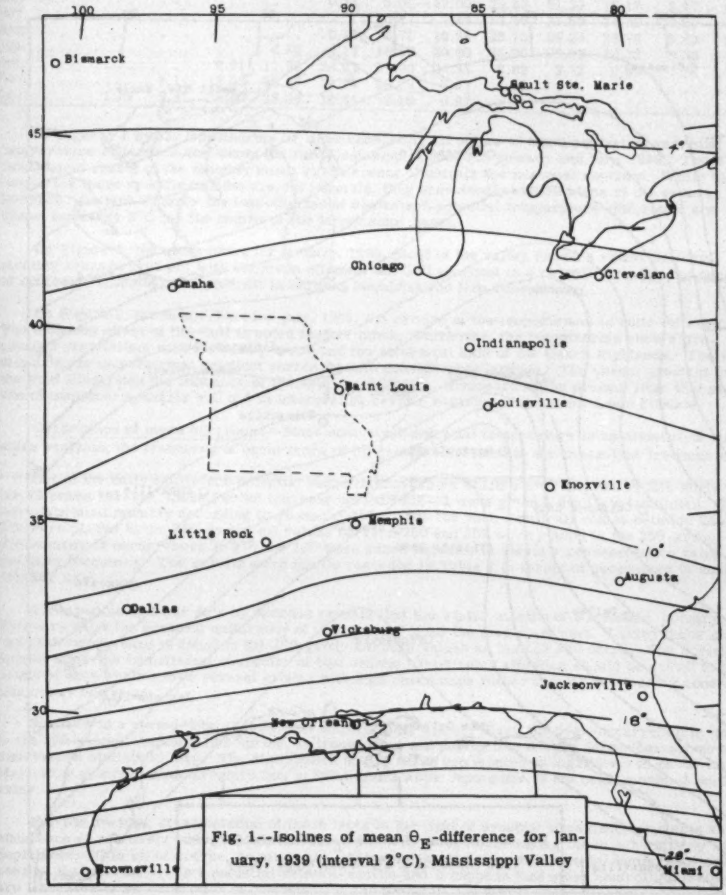

Fig. 1--Isolines of mean θ_E-difference for January, 1939 (interval 2°C), Mississippi Valley

temperature-difference, defined as the equivalent-potential temperature minus the dry-air temperature, (θ_E - T).

The mean θ_E difference rises from 6°.1 C in January to 35°.9 C in July. These values reflect the small pressure-change, the large temperature-increase, and most especially the moisture-increase in the surface air from winter to summer. Of course, this represents the total effect whether it be due to local physical processes or to the importation of properties from some other climatic province. Such importation of properties governs the dependency of climate on air-mass activity which contributes so much to the local aperiodic variability of the weather elements.

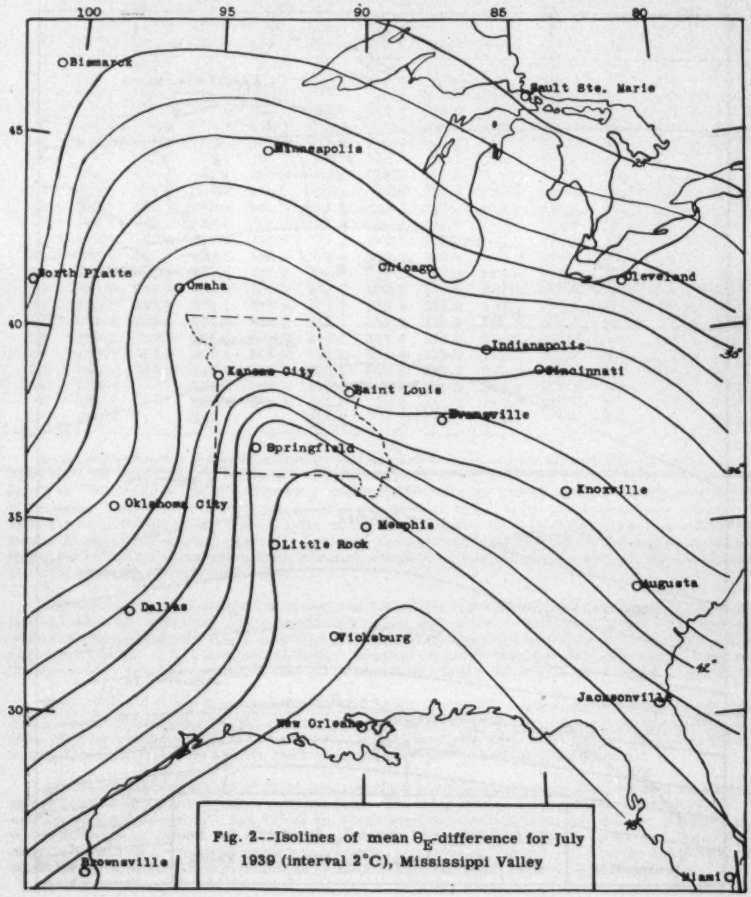

Fig. 2--Isolines of mean θ_E-difference for July 1939 (interval 2°C), Mississippi Valley

Table 2--Percentage-distribution of θ_E by groups (1932-41), Saint Louis, Missouri

Month	Group												
	240	250	260	270	280	290	300	310	320	330	340	350	360
Jan.	0.48	5.82	13.09	28.43	34.25	14.05	2.75	0.97	0.16	....	....	....	....
Feb.	0.18	3.72	12.39	33.81	32.21	9.91	5.31	1.77	0.71	....	....	....	....
Mar.	....	....	3.55	20.48	31.45	23.87	12.90	5.65	1.61	0.48	....	....	....
Apr.	....	....	....	2.67	18.03	31.55	24.21	16.36	6.18	0.83	0.17	....	....
May	....	....	....	....	1.29	9.87	27.99	23.62	24.11	11.33	1.78	....	....
June	....	....	....	....	....	0.33	5.00	18.00	25.83	31.33	16.17	3.17	0.17
July	....	....	....	....	....	....	0.97	7.43	17.45	31.50	34.89	7.59	0.16
Aug.	....	....	....	....	....	0.16	2.75	10.98	22.13	29.24	28.76	5.49	0.48
Sep.	....	....	....	....	0.17	6.17	18.50	20.50	24.00	20.00	10.33	0.33	....
Oct.	....	....	....	0.81	11.95	24.07	25.69	24.23	8.89	3.72	0.65	....	....
Nov.	....	....	3.17	19.00	36.17	24.16	10.67	5.67	1.16	....	....	....	....
Dec.	....	1.29	9.35	29.19	36.29	16.61	6.29	0.97	....	....	....	....	....

In Figures 1 and 2, isapotherms or lines connecting all points of equal equivalent-potential temperature-difference are shown for the Mississippi Valley for January and July, 1939. These isapotherm charts of the monthly mean θ_E difference illustrate the seasonal contrast. While the values for these specific months are not normals, they undoubtedly exhibit some of the general features. On both Figures the isapotherms of equivalent-potential temperature-difference are drawn for every 2°C for the region of the Mississippi Basin.

On Figure 1, the mean chart for January, 1939, most of the valley shows a rather uniform monthly average gradient with the mean effect of the Gulf confined to a coastal strip for the zone of maximum isapothermal gradient is between Memphis and New Orleans.

On Figure 2, the mean chart for July, 1939, the pattern of the isapotherms is quite different. The monsoon effect of the Gulf is noted farther north. Moreover, the isapotherms show a pronounced parallelism with the valley-trend and the structural axis of the Ozark Highlands. The zone of maximum isapothermal gradient varies through considerable latitude. The abrupt gradient to the west illustrates the influence of the semi-arid plains. It appears at the present time that proper use of isapotherm-charts will aid in interpreting certain vagaries of the Saint Louis climate.

Occurrence of mean θ_E groups--Since equivalent-potential temperature is an element of air-mass analysis, the frequency of occurrence of θ_E groups is related to air-mass-type frequencies.

Out of the daily equivalent-potential temperature-values which were compiled in this study for the 30 years 1913-42, those for the ten-year period 1932-41 were given a separate treatment. They were tabulated monthly according to groups of 10°. Thus for each month all values between 240 and 249 were placed in the 240-group, all values between 250 and 259 were placed in the 250-group, etc. The number of occurrences at 07^h and 19^h were added together to obtain a representative value of the daily frequency. The results were finally recorded in Table 2 in terms of percentage of each monthly total.

Examination of these data by seasons reveals that the winter months of December, January, and February show the greatest uniformity of distribution of all the major seasons. During these months the peak-occurrence is found in the 280-group although values as high as 320 occur. The spring months show the transitional character of that season. Particular attention should be called to the month of May which shows several groups with high percentage rather than an outstanding concentration in any one group.

Summer is a period only slightly less uniform than winter. Here the peak-occurrence is found in the 330-group. Autumn, like spring, is transitional and during this season September shows a distribution similar to May. The distribution during these two months is significant in so far as May is the month of peak-precipitation in Saint Louis while September is the peak-month of the fall rains.

For the present, contemplation of these facts in the light of synoptic experience suggests an abundance of relatively pure tropical maritime air over Saint Louis during the months of May and September. This is, of course, an air-mass interpretation of a very fundamental meteorological concept that marine air is a potential rainfall-source and it happens that other controlling factors are favorable to the promotion of condensation and precipitation during these months.

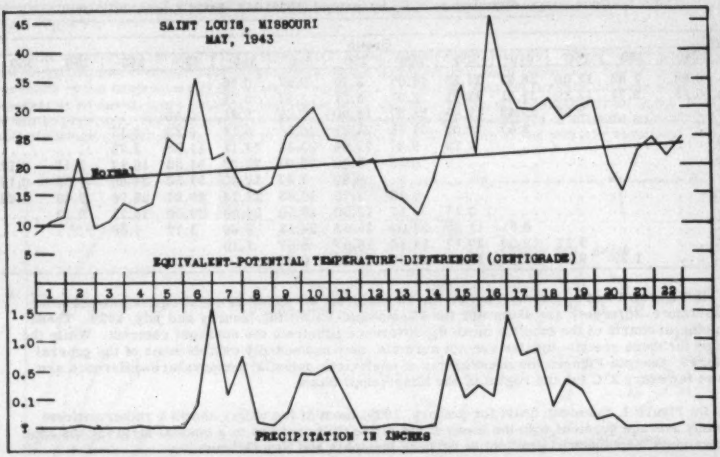

Fig. 3--θ_E-differences in °C for 07^h and 19^h, May 1-22, 1943, and 30-year normal values (upper) and 12-hour totals in inches of rainfall, May 1-22, 1943, Saint Louis, Missouri

Some equivalent-potential temperature-relationships--An interesting synoptic relationship of θ_E and rainfall can be seen in the Saint Louis weather data of May, 1943, plotted in Figure 3. The values of the observed θ_E difference in °C for 07^h and 19^h for the interval May 1 to 22, 1943, are plotted on the upper chart together with the 30-year normal values of the difference. The 12-hour totals of precipitation in inches are on the bottom chart.

It can be seen that the heaviest precipitation occurred whenever the observed difference was above normal. Examination of the analyzed maps of the United States Weather Bureau for this interval showed that whenever the difference was above normal the region about Saint Louis was occupied by a maritime air-mass either at the surface or aloft. Most of the time this air-mass

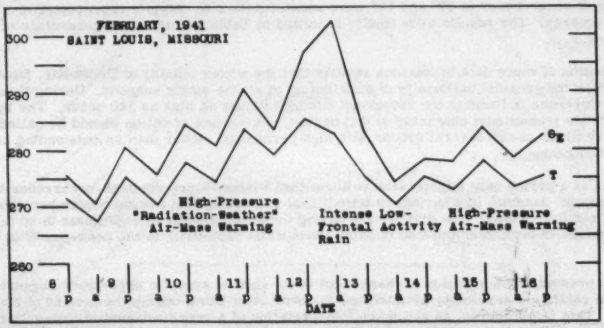

Fig. 4--Dry-air temperatures in absolute °C (lower) and computed θ_E for same observations, February 8-16, 1941, Saint Louis, Missouri

was tropical. When the difference was below normal the station was surrounded by polar continental air. Precipitation occurred as air-mass showers during the periods of high difference or as frontal rainfall or showers at the beginning or end of periods of high difference. It is to be understood that no direct causal correlation is implied between the value of the θ_E difference and the fall of rain. Both are observed phenomena with presumably common causes.

As a final note of this preliminary investigation of mean surface equivalent-potential temperature at Saint Louis, Missouri, another phenomenon should be mentioned.

In examining the various sheets of computation of equivalent-potential temperature it was surprising to notice how often during the winter months the θ_E value of a definite observation foreshadowed the air-temperature value 12 or 24 hours later.

Such occurrences are illustrated in Figure 4 by some data of February, 1941. Two quantities are plotted on this chart; the lower curve gives the dry-air temperature for the observations at 07^h and 19^h at Saint Louis University from February 8 to 16, 1941, while the upper curve is the computed value of the equivalent-potential temperature for the same observations. The abscissa of the graph gives the date and time of observation; the ordinate is in °A.

Notice, for example, that the value of θ_E at 07^h on February 14, 1941, was 274°.5 A and the value of the air-temperature at 19^h on the same day was 275°.2 A. This is a case of 12-hour foreshadowing within 1°; many such occurrences checked within 0°.1. Note also the value of θ_E at 07^h on February 14, 1941, was 278°.2 A, while 24 hours later the air-temperature at 07^h on February 15, 1941, was 278°.0 A.

Occurrences of foreshadowing within 1° are found most frequently in winter (there were 16 noticed in February, 1941); some are observed in fall and spring, but none are found in summer. This would be expected since the value of the equivalent-potential temperature-difference is so large in Saint Louis in the summer that it would require an impossibly large rise for the dry-air temperature to reach the θ_E value.

Apparently these occurrences are an expression of the activities of solar radiation, turbulence, etc., in the diurnal warming or accumulative warming of air-masses. They are generally associated with the passage of anticyclones over the Saint Louis area. The passage of such highs in winter is often the barometric indication of a surge of polar air from the north. In the front of the high-pressure center where the winds have northerly components this polar air possesses low values of equivalent-potential temperature which are gradually raised by acquisition of properties from the new climatic environment into which the air-mass penetrates. As the high passes eastward, the surface air becomes warmer and the warmest air is found in the rear of the center where the winds have southerly components.

Conclusion--In order to evaluate the air-mass factor in the Saint Louis climate, a preliminary attempt was made to apply a combination of climatological and synoptic techniques to the analysis of data of the Saint Louis University Meteorological Observatory. Daily values of the surface observations of temperature, pressure, and dew-point for the years 1913-42 were utilized for the calculation of daily mean surface equivalent-potential temperatures. A smoothed 30-year normal curve of this latter quantity was obtained by means of a Fourier analysis.

A comparison of the actual surface equivalent-potential temperatures for the period 1932-41 with the normals indicated the variability of the air-mass climate of Saint Louis. The departures from normal are real characteristics of the climate. The contrasts of the four major seasons are emphasized by tabulated quantitative data. Winter is the time of greatest mean uniformity while spring and autumn are transitional intervals. The air-mass climate is highly continental in winter but shows an increasing tendency toward a maritime character with the approach of summer.

The moisture-potential of maritime air as well as other physical and dynamic factors is important in governing the occurrence of precipitation at Saint Louis. The dependence of rainfall on the presence of tropical maritime air is especially pronounced in May and September, the months of peak-precipitation. It is suggested that the presence of tropical maritime air over Saint Louis during these months is due to the opportune positions of the semipermanent pressure-centers over land and sea, particularly the location of the Azores-Bermuda cell over the Atlantic.

Equivalent-potential temperature-difference was introduced for making air-mass climatic comparisons between selected stations of the Mississippi Basin and the results, although quite sketchy, warrant a further use of this quantity in air-mass climatology. Moreover, after further

study this value may prove useful in the prediction of temperatures which result from accumulative warming due to radiative and turbulent transitions of the surface layers of air-masses.

Acknowledgments--The author is indebted to Reverend JAMES B. MACELWANE, S.J., for his encouragement and advice, which guided this study through many troublesome phases. He is especially thankful to Reverend THOMAS M. KNAPP, S.J., for the loan of an additional Marchant calculator which greatly speeded computation, and to VINCENT F. JENNEMANN who assisted in the computations until he was called to active military service.

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TRENDS AND SINGULARITIES IN THE MEAN TEMPERATURE-DATA OF SAINT LOUIS, MISSOURI

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The results of a number of investigations in the past 20 years have aroused discussion [see 1 of "References" at end of paper] regarding the significance of certain climatic trends and singularities. During a recent study of mean temperature-data of the Saint Louis University Observatory some notes were compiled which may be of interest relative to these questions.

Trends--MARVIN'S [2] adaptation of Fourier analysis was applied to the daily mean temperature-data of the University Observatory for the period 1911-35 to obtain smoothed station-normals. It is interesting to compare the results of this analysis with those of two previous Saint Louis analyses; one by SCHOTT [3] who analyzed ENGELMANN'S [4] data for the period 1836-70, the other by MARVIN [5] who analyzed Saint Louis Weather Bureau data for the period 1875-1921.

Table 1--Comparison of calculated annual mean temperature-curves at Saint Louis, Missouri

Value	Schott (1836-1870)	Marvin (1875-1921)	Heinrich (1911-1935)
Maximum	78°.5 F	79°.1 F	80°.6 F
Date of maximum	July 24	July 26	July 25
Minimum	30°.3 F	30°.5 F	31°.6 F
Date of minimum	Jan. 13	Jan. 15	Jan. 14-15

Data on the extremes of the respective curves are given in Table 1. While the times of the maximum and minimum show fair agreement, the results reveal an increase in the value of the maximum and minimum of each succeeding study.

Moreover, a comparison of the monthly mean temperatures for the period 1836-82, averaged from the observations of ENGELMANN, and those for the period 1911-35, averaged from the observations of the University Observatory (Table 2), shows a net increase in the latter data especially for the months of September, October, November, and December. The use of the word net implies that there were departures from the general trend of increase even during the months of the interval from autumn to early winter. The net trends of the other months appear stable, since the differences between the two periods of observation amount only to fractions of a degree. More detailed techniques of the type used by GEDDES [6] for Aberdeen are required to indicate what, if any, variations or fluctuations have resulted in these small net differences.

Table 2--Comparison of observed normal mean temperatures by months

Item	Jan.	Feb.	Mar.	Apr.	May	June
	°F	°F	°F	°F	°F	°F
St. Louis University	32.3	35.4	44.2	56.0	65.9	75.3
Engelmann	31.8	35.4	43.7	56.8	66.3	74.7
(S - E)	+0.5	0.0	+0.5	-0.8	-0.4	+0.6
Item	July	Aug.	Sep.	Oct.	Nov.	Dec.
St. Louis University	80.2	77.4	70.9	58.7	46.2	35.3
Engelmann	79.2	76.8	69.0	56.1	42.8	33.4
(S - E)	+1.0	+0.6	+1.9	+2.6	+3.4	+1.9

Compilation of the 20-year moving summations of the annual means from 1930 to 1940 shows an increase for the year as a whole (Table 3). This is a continuation of the upward trend noted by KINCER at Saint Louis and other observation points.

Table 3--Moving summations of annual means of Saint Louis University temperature-data for 20 years ending with given year

Year	Summation	Year	Summation
1930	1122.5	1936	1131.8
1931	1123.8	1937	1134.1
1932	1126.5	1938	1137.6
1933	1127.7	1939	1139.3
1934	1130.3	1940	1139.4
1935	1130.8		

Since 1836, Saint Louis has grown from a small town to a metropolitan area with a population well over a million. The question naturally arises whether the increase in temperature has been due to urban growth. ENGELMANN did note an increase in temperature in the early rapid rise of the city. However, it should be noted that the increases in recent years have not been coincident with the periods of fastest growth of the city.

All the University temperature-data used in this report were taken at the same instrumental location in mid-town Saint Louis. Data by ENGELMANN and the Weather Bureau were obtained about two miles east in downtown Saint Louis. A comparison of the University data for the period 1911-35 with the data of the Weather Bureau for the same period shows that University means are generally lower than the Weather Bureau means although University data of this period are higher than the Weather Bureau values of earlier periods.

Singularities--The difficulties of interpreting singularities are universally recognized. MARVIN [2] in 1919 discussed singularities as harmonic components and aperiodic irregularities of the annual mean temperature-curve. He concluded that "The Fourier series, as applied to annual temperature data, converges only to the second term." As a consequence, he stated "Any systematic departures which may ultimately be disclosed by very long records will not be of periodic character."

If the temperature at Saint Louis (or any other station) is primarily controlled by the effective solar radiation, it is reasonable to suppose that the normal mean temperature-curve would be an harmonic curve with a dominant annual period. Modifying influences, exerted by seasonal variations of circulation and local temperature-controls, are likewise a function of solar radiation and could be periodic with an effective annual period.

These physical considerations suggest the possibility of temperature-variations of the same annual period which differ in amplitude and mutual phase-relations due to the lag-effects of the minor regional and local temperature-influences. It is here that the mathematics of the Fourier analysis fails to reveal the physical reality of the possible annual variations which may differ from each other in phase or amplitude. Since the usual technique of analysis consists in finding the best fitting sine- and cosine-terms of annual period, it does not necessarily follow that the sine- or cosine-term of fixed phase finally determined as the annual component is the only possibility. The annual-component term eventually put into the equation for the mean temperature may be a good fit; but it is not a uniquely determined harmonic. An observed set of data which can be

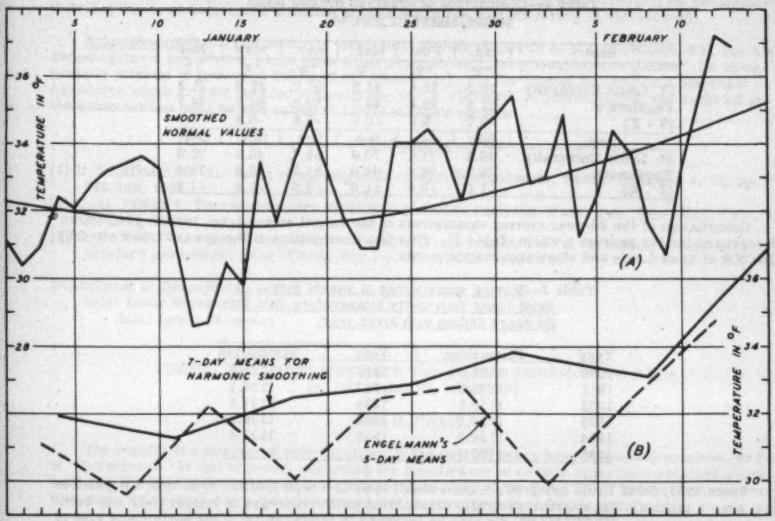

Fig. 1--Averages of observed daily mean temperatures, Saint Louis University Observatory, 1911 - 1935 (upper); seven-day means daily mean temperatures during minimum period, Saint Louis University Observatory, 1911 - 1935

approximated by a function of the form $y = K \cos (mx + f)$ may in reality be made up of several components of the same period but of different phase and amplitude.

It seems reasonable to suppose that in the chain of events leading up to the observed annual temperature-march there could be some components of annual period produced by terrestrial lag-effects. EDWARD H. BOWIE [7] in 1935 emphasized the retardation of the extremes of temperature (the so-called thermal solstices) after the astronomical solstices as outstanding effects of terrestrial control which he stated are peculiar to each observing station. Moreover, a lag-effect was noted by MARVIN in 1919 in the Saint Louis Weather Bureau temperature-data. After analyzing the daily maximum and daily minimum temperatures separately, he found that the amplitude of the second harmonic in the Fourier equation is much larger in the maximum temperature than in the minimum temperature.

It appears that explanation of the character of the annual temperature-curve requires a consideration of the terrestrial lag-effects. This is particularly true of the curve in the neighborhood of the annual extremes. With specific reference to the Saint Louis University data, the annual mean temperature-curve does not show symmetric extremes. The maximum and minimum on the smoothed curve are a sort of average of the fluctuating values, so that the "normal maximum" and "normal minimum" do not occur on the observed warmest and coldest days of the year.

SLOCUM [8] in 1941, in attempting to interpret the fluctuating character of the mean temperature-curve of Washington, D. C., at the time of the minimum, added new evidence for the reality of the January Thaw. In his analysis he used a different approach from that of NUNN [9] in his study in 1927 of the January Thaw. Moreover, SLOCUM notes the existence of a cold period in the Washington data on about February 5. This cold period was suggested by ENGELMANN in his pentad analysis in 1886 of the Saint Louis data when he wrote: "It will be seen, however, that the means of these periods do not progress, rise and fall much more evenly than the single daily means; compare, e.g., the mean of January 31 to February 4, which is so much lower than the mean of the

Table 4--Twenty-five-year averages of daily mean temperatures at Saint Louis, Missouri, during intervals of annual maximum and minimum and distribution in reference to calculated normal values

Date or item	Temperature	Date or item	Temperature	Date or item	Temperature
	°F		°F		°F
		December - January			
24	34.1	1	31.1	9	33.6
25	30.1	2	30.4	10	33.3
26	30.9	3	31.0	11	31.2
27	29.2	4	32.4	12	28.6
28	29.7	5	32.1	13	28.7
29	31.6	6	32.8	14	30.5
30	34.8	7	33.2	15	29.8
31	33.2	8	33.4	16	33.5
		July			
11	80.6	18	80.3	25	80.4
12	80.6	19	80.0	26	80.7
13	82.1	20	80.4	27	81.9
14	80.2	21	81.7	28	82.2
15	80.4	22	80.6	29	81.1
16	80.3	23	81.1	30	80.4
17	79.8	24	80.8	31	79.6

Date	Dec. 27	Dec. 28	Jan. 12	Jan. 13	July 13	July 28
Normal value	33.0	32.8	31.6	31.6	80.2	80.2
Days						
Normal	1	0	1	0	3	2
Above	10	11	8	11	16	17
Below	14	14	16	14	6	6
Total	25	25	25	25	25	25

foregoing or the following five days that one might suspect a regular and normal decline of temperature in these days, and not mere accident."

In the lower diagram of Figure 1, the averages of pentad temperature of ENGELMANN for the period 1836-82 and the seven-day averages of the Saint Louis University data from 1911-35 have been plotted for the interval January 1 to February 14. The general character of the two curves is similar--they both illustrate the rise in late January and the decline in early February. However, the curve of recent data is generally higher and the peaks and dips occur on different dates on the two diagrams.

In the upper diagram of Figure 1, the smoothed harmonic normal mean temperatures and the observed daily 25-year averages of the University data have been plotted. The observations of the last week in January do lie above the normal curve and the data for the early part of February generally lie below the normal; but it is difficult to fix the date of peak-deviation. From a physical point of view it seems better to describe the phenomena as recurring period-tendencies.

One last point in regard to the possibility of several annual components of differing phase or amplitude. The Saint Louis data furnish a particularly attractive suggestion. Mindful of the warning to beware of the pitfalls of inflexion hunting, the author believes that the low period which occurs about December 27 in the data of Table 4 is worthy of investigation. This low period which occurs some 15 or 16 days prior to the observed annual minimum on January 13 acquires significance when viewed with the high period which is found 15 or 16 days prior to the observed annual maximum on July 28.

Even though extended observations might tend to reduce the prominence of this type of inflexion, their effects on the annual mean temperature-march might still be apparent in the flattening of the annual curve during the periods of highest and lowest means.

Acknowledgments--In closing, I wish to thank Reverend JAMES B. MACELWANE, S.J., for his advice and interest in this work; to express my appreciation to Miss MARIE McKINNON, who did a great part of the transcribing and checking of original data, to LE ROY S. BUCKIE who aided in many of the computations, and to all others who assisted me at different times during the study.

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PROGRESS-REPORT ON MOUNT WASHINGTON ICING PROGRAM

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This paper concerned war work and may not, therefore, be published at the present time.

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COMPARISON OF AIR-MASS MAPS WITH PRECIPITATION-RECORDS

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There are many ways in which the data on air-mass maps may be correlated with precipitation-records but this paper deals only with the mapped position of fronts on two successive days and the correlation of this position with time and magnitude of precipitation.

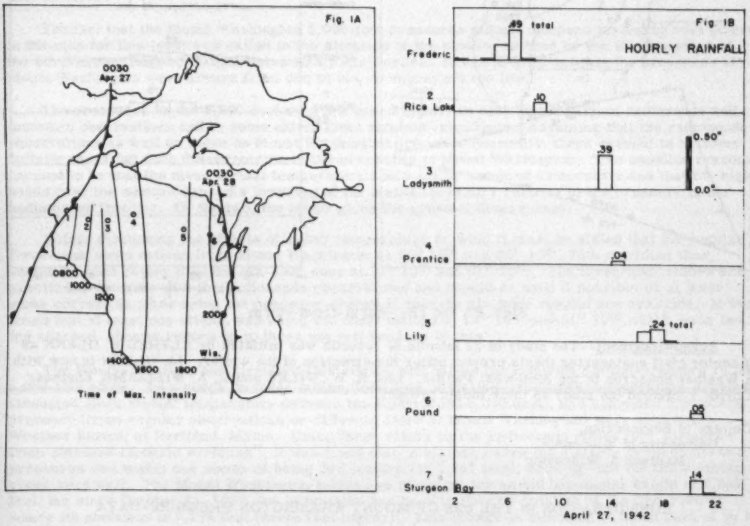
Cold-front storm--A more or less typical cold front, as it moved across the State of Wisconsin on April 27, 1942, is shown in Figure 1A. The positions of the front are indicated as taken from the daily weather maps for April 27 and 28.

On this same map the time of precipitation was indicated for 54 Wisconsin stations plus a few in adjoining States, all in the upper Mississippi Hydrologic Network. Generally the rain fell within one calendar hour and was indicated as falling at the mid-point. The time-contours shown were then drawn to indicate the time at which the rain fell in different portions of the State. As is to be expected, the rainfall-movement was reasonably regular and faster across the southern part of the State than across the northern. Since the front at $00^h\ 30^m$ on April 28 is indicated as being above ground, it is not contradictory that the rain fell along the Lake Michigan shore some four or five hours earlier.

The data for a series of seven stations taken at approximately right-angles to the time-contours are shown in Figure 1B. It indicates for a typical cross-section of the storm the variation in amount of rainfall that was experienced as well as the time of travel of the rain-wave.

Warm-front storm--Data for a warm front was plotted similarly in Figure 2. In this case the time of beginning and end of rainfall was not so well defined as at many stations there were several hours with only 0.01 inch of rainfall each at the beginning or end of the rain. Times indicated on the contours are nevertheless the mid-point time between the beginning and end of rain--so well as it could be determined.

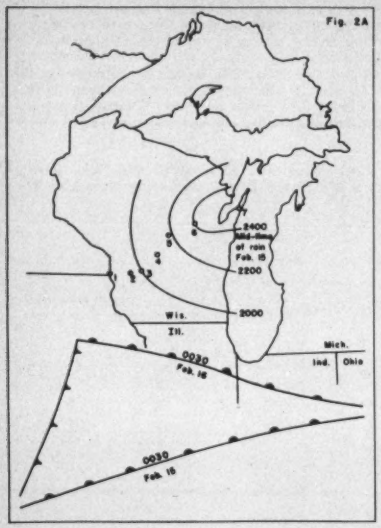
It is interesting to note that the front pivoted about a point in north-central Ohio. The more active movement was therefore in the western part of Wisconsin and the rain-wave showed a corresponding increase in speed in this region.

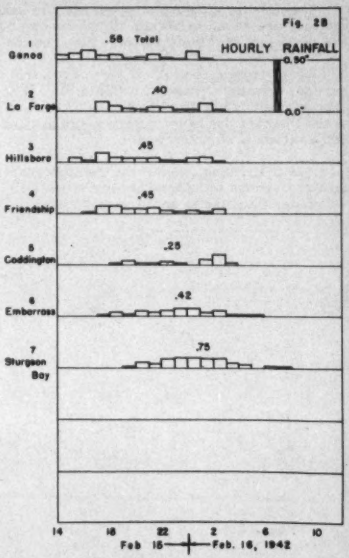


Figs. 1A and 1B--Cold-front storm

Conclusions--Except for the obvious conclusion that the rainfall occurred as would be expected from the movement of the fronts, the most important conclusion that can be made is that typical examples like the above are more rare than might be expected. Data for 22 months were studied with but 20 storms sufficiently well defined to permit plotting. Many of these were occluded fronts and so involved to preclude their use as an illustration.

These storms have been used to illustrate to the class in hydrology the different character of warm-front and cold-front precipitation. It is hoped their presentation will encourage a study by others of better data with movement over greater distances.





Figs. 2A and 2B--Warm-front storm

Acknowledgment--The study of 22 months of records was initiated by ALFRED H. GLENN as a senior civil engineering thesis project under the direction of the writer. Lt. GLENN is now with a Weather Squadron in the Southwest Pacific. Lts. R. W. WILKE and G. A. WILLIAMS, Engineer Corps, continued the study as their thesis project.

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CONSIDERATION IN THE USE OF MOUNT WASHINGTON PRESSURE-DATA

Raymond E. Falconer

It has been realized for some time that the barometric pressures as observed on Mount Washington have tended to be lower than would be expected. The sea-level pressures as reduced from station-pressures have never been considered to be of any accuracy but have been put on the teletype more as a matter of form than for any particular value they might have. It was only recently learned that the 5,000-foot pressures from this station do not fit into the maps drawn for that level. This fact seemed to be good reason for studying the possible causes.

It is generally known that the reduction of station-pressure to mean sea-level pressure becomes less accurate the higher the station is above sea-level. For stations at elevations of 1,000 feet and less, this reduction is reasonably accurate but for stations of greater altitude the correction becomes more and more inaccurate and sea-level pressures thus obtained seldom fit into the surface weather-map.

In reducing pressure to sea-level it is necessary to consider the density, temperature, and moisture-content of a column of air directly below the station down to sea-level. Since such an air-column is assumed to exist where actually there is a mass of land, the temperature and moisture-content of the column can be only hypothetical and are subject to great inaccuracies. The assumption of the mean virtual temperature gives the most difficulty, as temperatures at such greatly separated levels are subject to wide variations due to the local effects of the surrounding land and the air-mass itself. In the case of Mount Washington the error in mean virtual temperature between the summit and sea-level in extreme cases can be as high as 15°F. Such an error would result in a discrepancy of approximately four to six mb.

The above is mentioned because reports are continually being received of fruitless attempts to use Mount Washington sea-level pressures. The same is true of other stations of high elevation, especially those in the western mountains. It should be pointed out that, even though these pressures do not fit the map, many of the other data contained in the synoptic report are of value and the whole report should not be discredited simply because these sea-level pressures are unavoidably in error.

The fact that the Mount Washington 5,000-foot pressures did not compare favorably with others in the map for this level was called to the attention of the observers here by the Headquarters of the 8th Weather Region, United States Army Air Forces. It was pointed out that the pressures at Mount Washington were always from one to ten, or more, mb too low.

The pressures on the 5,000-foot map are based mostly on data obtained from radiosonde and mountain observations and to some extent from airplane-soundings. Assuming that the radiosonde observations as well as those on Mount Washington are made correctly, there seemed to be some definite cause for such discrepancies in the pressures at Mount Washington. Two possible reasons seemed to be that the mean virtual temperature could not be assumed as accurate and that the high winds over the summit caused a lowering of the station-pressure relative to the pressure in the undisturbed free air. Of the two, the latter gives the greatest discrepancy.

Before discussing the effects of either temperature or wind it must be stated that the regular three-hour observations from Mount Washington at $10^h\ 10^m$ and $22^h\ 10^m$, 75th meridian time, should be used rather than the six-hour ones at $13^h\ 10^m$ and $01^h\ 10^m$. The three-hour values are practically synoptic with the radiosonde observations and should be used if possible or at least some correction made using the pressure-change if only the six-hour results are available. It was found that at least one station was using the observations at $13^h\ 10^m$ and $01^h\ 10^m$ which, upon being checked, showed errors up to three mb just because of this.

The Weather Bureau has furnished this station with tables for reducing station-pressure to the 5,000-foot plane. As a check on these tables, four sets of station-pressures, temperature-argument (assumed mean virtual temperature between the summit and 5,000-feet), and computed 5,000-foot pressure (from regular observations on different dates at Mount Washington) were sent to the Weather Bureau at Portland, Maine. Using these values on the radiosonde tables for "distances from standard isobaric surfaces", it was found that in all four cases the distance between the two pressures was within one meter of being 386 meters (or 1,267 feet), showing that the two methods check very well. The Mount Washington tables are made out for an old barometer height of 6,267 feet, but since October 21, 1937, the barometer has been in the new building of the Observatory where its elevation is 6,274 feet (seven feet higher). This change in elevation is taken care of by a +0.006-inch correction, which is applied to all readings of the barometer.

The practice of the Weather Bureau in obtaining the temperature-argument or mean virtual temperature for use with the above tables is to add the temperature of six hours previous to twice the current temperature. To the mean of this sum is added a lapse-rate correction of +2°F in the particular case of Mount Washington. Twice this, or 4°F, gives the assumed average difference in temperature between the summit of Mount Washington and the 5,000-foot level. The Weather Bureau adopted the lapse-rate correction because certain aerological data at hand indicated that the diurnal variation in lapse-rate was thereby provided for (to some extent) even though a constant lapse-rate was assumed. In other words, the rule gave results which approached the current mean temperature of the air-column.

Having shown that the tables in use at the station are accurate and that the lapse-rate correction used is a representative normal, let us consider what effect temperatures have on the temperature-argument or assumed mean virtual temperatures between the levels in question. In the case of a cold-front arrival the temperature on the summit might have been 42° six hours before while the current temperature had dropped to 11°. Then the temperature-argument used according to the practice of the Weather Bureau would be

Current temperature	11°F
Current temperature	11
Temperature six hours before	42
Sum	64
Mean	21
Lapse-rate correction	2
Temperature-argument	23

If the station-pressure happened to be 23.702 inches, then using the temperature-argument of 23°F the tables show that the correction to be added to the station-pressure to give the 5,000-foot pressure is 1.194 inches. Now actually the current temperature at the 5,000-foot level was probably near 15°F, so that the mean virtual temperature that should have been used was the mean of the current temperature of 11°F at the summit and the 5,000-foot temperature of 15°F, or 13°F. From the tables it is found that the correction for this temperature is 1.221 inches. The pressure thus obtained for 5,000 feet will then be 0.029 inch higher by using the temperature of 13°F. This is an extreme case and it seldom happens that such a sharp temperature-drop will be noted, but in this extreme the greatest error possible seems to be about 0.029 inch, or about one mb. Using a pressure of 24.80 inches this difference is 0.028 inch, and at 22.50 inches a difference of 0.025 inch, showing there is little change in tabular values for varying pressures and constant temperatures.

If a cold front had just reached the 5,000-foot level, while the summit was still in the warmer air, there might have been the condition that the latter point had been at a temperature of 10°F six hours before and currently is at 9°F, making a temperature-argument of 11°F. At the same time the temperature at the 5,000-foot level might have actually dropped from 15°F to -10°F (in an extreme case). With the current temperatures of 9°F and -10°F at the summit and at 5,000-foot levels, respectively, the actual mean virtual temperature-argument used should have been the mean of these two temperatures, or 0°F. In other words, the temperature-argument as computed was 11° higher than in the actual case. At a pressure of 23.702 inches the correction at 11° is 1.226 inches and at 0° it is 1.257 inches. The difference amounts to 0.031 inch, or an error of about one mb due to the difference of 11°F between assumed and actual mean virtual temperature

Take the case of a warm-front passage bringing the summit into a warmer air-mass while the 5,000-foot level is still in the cooler air. Before the front passage the temperatures at 5,000 feet and at the summit might have been 15°F and 11°F, respectively. Six hours later the summit is under the influence of the warmer air-mass with the temperature rising to 25°F. The computed temperature-argument as obtained by the method of the Weather Bureau would be 22°F. But the 5,000-foot level still is in the cooler air with a temperature of 15°F so that the actual mean temperature would be the mean of the current temperatures of 25°F and 15°F, or 20°F. From the tables, it is found that the difference of only 2°F between the assumed and the actual temperature-argument gives a difference in correction used of only 0.005 inch, or less than 0.2 mb. A small correction for the water-vapor content of the air ordinarily used with these tables has not been used in the discussion.

It appears then that in the most extreme cases the computed temperature-argument is not much more than 10°F in error from the actual mean virtual temperature. The tables show that the error for a difference of 10°F in temperature at any pressure varies from 0.030 inch between -20°F and -10°F to 0.020 inch between 50°F and 60°F, or one mb or less for every change of 10°F in temperature at a given pressure. In other words, errors in the computed 5,000-foot pressure at Mount Washington should have an error less than one mb because of non-representativeness of the computed temperature-argument. An error of much over 10°F would seem to occur only in the extreme cases, such as with the arrival of a cold front.

Of course, in this paper the discrepancies in 5,000-foot pressure are being compared with the pressures in free air at that level as obtained by radiosonde. The pressures from the radiosonde method are generally believed to be accurate within one mb, although greater errors may exist at times (see MIDDLETON and KNOWLES in Meteorological instruments, Chap. 10, Sec. 11, p. 205). A mean monthly average of the radiosonde data, however, would probably cancel out these errors, resulting in a pressure-value that is as near accurate as can be obtained with instruments now in use.

So it would seem that the errors in pressure at Mount Washington due to the previously discussed reasons are within the same limits of accuracy as the pressures obtained in the free air by radiosonde.

As is well known, the Venturi tube is based on the principle that if a fluid passes through a pipe or tube of varying section, the pressure of the fluid will be less in the constricted portion than in the non-constricted portion. Since the same amount of fluid flows through each cross-section per unit of time, the velocity must vary inversely as the area of the cross-section. That is, its total energy is unaltered throughout the flow, and it follows that what it gains in kinetic

energy it loses in pressure-energy, the sum of the two always remaining constant. Then let us consider the effect of the wind in causing too low a barometric pressure on Mount Washington and the possibility that the mountain acts as a gigantic Venturi tube.

In a mathematical expression of these conditions for incompressible fluids we have

$$(P - p) = d\,[(A/a)^2 - 1]\,V^2/2g \qquad (1)$$

where P and p are pressures measured in the non-constricted and constricted parts of the tube, respectively, A is the area of the non-constricted portion, and a is the area of the constricted part, while d is the density of the fluid, g is the acceleration of gravity, and V is the velocity in the non-constricted portion of the tube [see GLAZEBROOK, Dictionary of applied physics, v. 3, p. 567].

If d, g, A, and a remain constant for a given case, it will be seen that the difference in pressure will be proportional to the square of the velocity so that $(P - p) \propto V^2$. And if d, g, and V remain constant for a given case, the pressure-difference will be proportional to the ratio $(A/a)^2$ or $(P - p) \propto [(A/a)^2 - 1]$.

Mount Washington and the Presidential Range, due to the average elevation of over 5,000 feet, offers a barrier of constriction to the free flow of air in the region. By comparing wind-velocities, it is found that the velocities on Mount Washington are considerably more than those in free air at the 5,000-foot level; thus the two major conditions necessary for the Venturi effect to exist at Mount Washington are fulfilled.

However, considerable difficulty arises when a mathematical adaptation of the equation for this effect is attempted. Assumptions involved in equation (1) are that an incompressible fluid is flowing in a frictionless horizontal pipe which it fills. In the free atmosphere, friction is present, the air-flow is not strictly horizontal and, of course, the air is compressible. In addition, the potential energy of the air, the atmospheric stability, and orographic effects become factors. A complete container for such an air-flow cannot be fully determined since the only fixed part of such an imaginable container is the surface of the Earth, which in itself is of non-computable area as in the case of the mountain acting as a constriction to the air-flow. At this point the difficulty of defining, from theoretical considerations, a Venturi effect caused by a mountain becomes obvious.

Further study will reveal, however, the possible trends that might be expected. In the ideal case, AV = av, where A is the cross-sectional area and V is the velocity of flow in the unconstricted part of the tube and a and v are similar elements in the constricted part of the tube. Thus, in the atmosphere the ratio (A/a) might be determined if V (free-air wind-velocity) and v (mountain wind-velocity) were known. Difficulties arising in such a computation would be the unpredictable effect of atmospheric stability, changes in potential energy, and friction on v. Further investigation into this phase of the problem has not been made at this time because its use in correcting mountain pressures for immediate synoptic use would be unwieldy and would depend on the existence of pilot-balloon and radiosonde observations from surrounding stations (often lacking where most needed). However, this possibility is suggested as a check on an empirical method (to be discussed later in this paper) and for use in emergency.

Further consideration of the relationship in equation (1) shows that certain characteristics of the atmosphere like instability, turbulence, etc., affect the ratio $(A/a)^2$, which would mean that the pressure-differences might not vary strictly as the square of the wind-velocity due to the lack of constancy of (A/a). From AV = av it is seen that, for a given ratio (A/a), V and v will be proportional. Assuming, for the moment, that friction and changes in lapse-rate and potential energy have a negligible effect on (A/a), consider the probable effect on (A/a) of varying wind-velocities. In the case of a pipe this ratio is constant. In the atmosphere, however, there is no "lid on the container" and it is reasonable to expect, on the basis of experience, that as the wind-velocities increase the ratio (A/a) will decrease because the barrier-effect of the mountain extends to higher levels. This is a fact well known to aviators who have flown over mountain terrain, although the effect cannot be considered to proceed in this fashion indefinitely since atmospheric stability imposes a damper to mechanical turbulence.

In summary, then, due to the difficulties discussed, mathematical computation of the exact theoretical Venturi effect on a mountain summit is impossible; but in approximation one should expect the Venturi effect on pressure-differences to vary at somewhat less than the square of the wind-velocity due to the decrease of (A/a) with increasing wind.

The extent to which the above considerations are sound and just how the unpredictable factors affect this suggested variation has been determined by the study of discrepancies based on the mean monthly 5,000-foot pressures for radiosonde observations and for Mount Washington. Thirty-six cases covering each month, for the years 1941-1942-1943, were considered and discrepancies were plotted according to the average wind-velocities at Mount Washington for the corresponding months.

The maps for the 1,524-meter (5,000-foot) level, as found in the Monthly Weather Review, were used for interpolating what the mean 5,000-foot pressure should have been on Mount Washington for each month. The values thus found were taken to 0.1 mb although the map is made up from data which were only taken to the nearest whole mb. The Mount Washington pressures were taken to the nearest 0.1 mb from the record of six-hour observations kept at this station and were chosen to be as close as possible to the time of the radiosonde observation. From January through September, 1941, radiosonde observations were taken at $00^h\ 30^m$, so the data at $01^h\ 10^m$ for Mount Washington were used. From October, 1941, through December, 1943, radiosonde observations were made at 20^h and comparative Mount Washington data were obtained by averaging the observations at $19^h\ 10^m$ and $01^h\ 10^m$. The average hourly wind-velocities for each month are recorded at the sta-

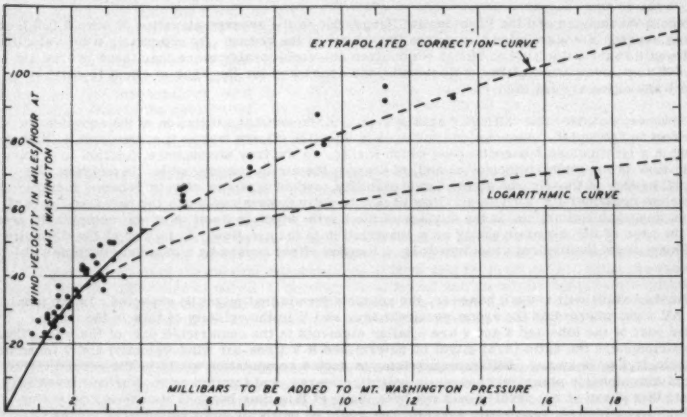

Fig. 1--Correction in millibars to be added to Mt. Washington, New Hampshire (elevation 5000 feet), pressure for varying wind-velocity (plotted points based on discrepancies between mean monthly radiosonde pressures at 5000 feet and corresponding pressures at Mt. Washington as against average wind-velocity there at same time)

tion and the values used were also taken for the hour nearest the time of the radiosonde observations. There were three cases where the discrepancies between the radiosonde and Mount Washington pressures did not fit into the expected results too well and, in checking the tabulated data in the Monthly Weather Review with the corresponding 1,524-meter maps for the months of March and September, 1941, it was found that the tabulated data did not fit well into the map. As the latter seemed to give more reasonable discrepancies, these values were used.

The resulting curve (see Fig. 1) shows what seems to be an excellent correlation and it follows very well the results that might have been expected from previous discussion. The correction from this curve was applied to Mount Washington pressures during the months of February, April, and the first half of May for the observations corresponding to the twice-daily radiosonde ascents. Using the Albany (New York) and Portland (Maine) radiosonde pressures and pilot-balloon wind-directions at 5,000 feet, it was found in everyccase that, with the correction, the Mount Washington pressure fitted almost perfectly into what would seem to be the reasonable isobar to expect. Of course, a complete map in all these cases was not available at the station, but it is doubtful that the corrected pressure would be more than one mb off in the complete map except possibly in

Table 1--Percentage of total number of cases with deviations from curve of indicated number of millibars or less

Less than	Pct cases	Less than	Pct cases	Less than	Pct cases
mb	pct	mb	pct	mb	pct
0.1	14	0.4	53	0.7	97
0.2	30	0.5	72	0.8	92
0.3	44	0.6	86	0.9	100

winds above 54 mph. With higher velocities the isobars would be closer together so that the relative error in actual miles from the correct isobar would probably be no greater than the error at lower velocities where the isobars have greater spacing.

The discrepancies based on monthly averages were correlated with a range in velocities of from 22 to 54 mph, so that velocities above and below this range had to be based on a few individual observations. In the range of velocities, 22 to 54 mph, a linear curve could be used, but for velocities over 54 mph, at least with the 14 individual cases available, the corrections necessary seemed to show that a curve somewhere between linear and logarithmic would be better. Further study will have to be made of individual cases with comparison of the discrepancies to the actual map for the particular time and date in order to be more certain of the exact shape of the curve at high velocities. With velocities below 54 mph, the discrepancies in all but one case deviate less than 0.7 mb from the curve. Vertical velocity-gradients and different free-air wind-velocities would have some variable effect on the correlation, although it is not now thought to be very great as seemed to be the case when corrections were applied to the observations of February, April, and May as previously mentioned. Consideration of the effect of wind on pressure within the building, due to small openings around doors, windows, etc., should be mentioned, although it is probable that this error is small except in high gusty winds, when pumping of the barometer occurs. Little can be done to eliminate this as the barometer must necessarily be inside the building and subject to this effect. When pumping occurs, the practice is to read the barometer at an average value.

In this connection the following statements are pertinent [see Trans. Amer. Soc. Civ. Eng., No. 105, paper 2095, Wind bracing in steel buildings: Final report of Sub-Committee No. 31, Committee on Steel of the Structural Division, pp. 1713-1739, 1940]. In these excerpts q represents the dynamic wind-pressure [$q = (1/2)(dv^2)$].

"Normally, air-leakage due to the usual small openings around windows, doors, skylights, and eaves will give rise to an internal pressure or suction of from 0.25 q to 0.35 q, depending on whether the openings are chiefly in the windward or in the leeward surfaces. In the rapid building up of gust velocities, the air-transfer may be so slow that the internal force is less than this. In standard N-790 of The Netherlands, the external wind-forces have all been adjusted to take account of an internal suction of 0.2 q.

"Where openings are of substantial size, the internal wind-force may be of considerable magnitude. It may be pressure or suction, depending on whether the openings are in windward surfaces, in leeward surfaces, or in surfaces parallel to the wind. Very large internal pressures have been, and may be, built up because of the breaking of windows on the windward size of buildings by reason of flying gravel from the roof or other objects carried by the wind."

Table 1 has been prepared to show what per cent of the total number of cases had deviations from the curve of the indicated number of millibars or less. Only cases in the range of 22 to 54 mph were considered and the deviation was divided about equally either side of the curve. It should be mentioned that this same correction, when applied to the Mount Whiteface (New York) 5,000-foot pressures, appears to work equally well. However, mean monthly data from that station could not be obtained in time to be plotted in the same manner as the Mount Washington data. Undoubtedly other isolated mountain stations will find a similar correction-curve which can be applied to their pressures and it would seem that such curves should be drawn in order to make their reports of more value.

Of course, it is obvious that the Venturi condition will also affect the pressure-change and pressure-tendencies so that the correction would necessarily be applied to these figures. Since the Mount Washington observations are available every three hours, it is felt that, with these applied corrections, the reports from this region would provide the forecaster with a means of more closely following the change in the 5,000-foot pressure-field between the times covered by the twice-daily maps now in use (see Table 2).

Further study is being made of Mount Washington pressure as influenced by wind-velocities. It is hoped this may be presented as a separate paper. Included in this presentation would be figures showing the pressure-correction plotted against the square of the Mount Washington wind-

Table 2--Change in 5000-foot pressure-field between times covered by twice-daily maps now in use

Month	1941				1942				1943			
	5000-ft pressure Mt. Washington		Discrepancy	Wind-velocity Mt. Wash.	5000-ft pressure Mt. Washington		Discrepancy	Wind-velocity Mt. Wash.	5000-ft pressure Mt. Washington		Discrepancy	Wind-velocity Mt. Wash.
	Interpolated, 1524-m map[a]	Reduced from station-pressure			Interpolated, 1524-m map[a]	Reduced from station-pressure			Interpolated, 1524-m map[a]	Reduced from station-pressure		
	mb	mb	mb	mph	mb	mb	mb	mph	mb	mb	mb	mph
Jan.	836.7	835.1	1.6	34	834.0	831.4	2.6	46	835.2	831.5	3.7	54
Feb.	829.4	827.1	2.3	42	827.7	825.3	2.4	42	832.0	828.8	3.2	50
Mar.	831.6	828.9	2.7	44	834.5	832.2	2.3	43	839.8	837.0	2.8	49
Apr.	844.2	842.7	1.5	29	842.5	840.5	2.0	28	837.2	834.3	2.9	39
May	841.7	840.4	1.3	28	847.8	846.2	1.6	28	845.9	844.2	1.7	28
June	846.6	844.7	1.9	31	847.3	845.7	1.6	22	847.2	844.3	2.9	36
July	848.2	847.0	1.2	23	848.3	846.8	1.5	25	848.2	846.5	1.7	24
Aug.	845.2	843.6	1.6	31	850.3	849.0	1.3	28	845.7	844.2	1.5	27
Sep.	848.0	845.8	2.2	34	848.9	847.5	1.4	26	849.7	848.9	0.8	23
Oct.	844.2	840.7	3.5	40	845.8	844.8	1.0	27	842.9	841.0	1.9	34
Nov.	839.2	837.6	1.6	37	840.3	837.9	2.4	41	841.1	839.0	2.1	36
Dec.	838.0	835.2	2.8	40	833.3	830.2	3.1	50	834.5	831.3	3.2	45

[a] As published in Monthly Weather Review and based on mean monthly averages of pressure and velocity at approximate time of radiosonde observations.

velocity and the square of the free-air velocity for 5,000 to 6,000 feet, based on pilot-balloon observations at nearby stations.

The writer wishes to acknowledge the great help given by VICTOR F. CLARK, Official-in-Charge at Mount Washington Observatory, in the preparation of this paper, and also to thank RICHARD L. DAY of the Weather Bureau Central Office and the staff of observers at the Portland (Maine) Weather Bureau for supplying much of the data used. Corrections suggested by D. M. LITTLE and L. P. HARRISON of the Weather Bureau Central Office at Washington and Dr. C. F. BROOKS of Blue Hill Meteorological Observatory, were greatly appreciated.

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STABILITY-SUPPRESSION OF TURBULENCE AS INDICATED BY DIURNAL CHANGE OF VELOCITY-PROFILE OVER SMOOTH GROUND

F. A. Brooks and W. P. Berggren

The typical diurnal oscillation of velocity-profile, such as shown in Figure 1, indicates by reduced velocity at night that there is greater resistance to air-flow near the ground because of thermal stability. Above 14 feet, however, the velocity gradients at night (as shown in Table 2) exceed the daytime magnitudes. This, in the case of unchanged shear-stress distribution, would indicate a nocturnal decrease in resistance to air-flow in a region a short distance above the ground. When the gradients are corrected for buoyancy-stability the indicated decrease in resistance is even greater.

It is to be noted that in the authors' [see 1 of "References" at end of paper] expression for velocity-gradient as affected by thermal gradient

$$(dU/dz) = \sqrt{(\tau_n/\rho \ell^2) - (g/\Theta)(d\Theta/dz)} \qquad (1)$$

the thermal-stability term may exceed the kinetic-turbulence term, in which case the radical becomes imaginary. If this critical condition can be taken to indicate suppression of turbulence by buoyancy-stability, it affords adequate explanation of the typical shape of the early morning velocity-profile.

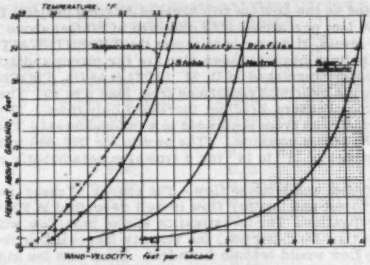

Fig. 1--Typical diurnal variation of velocity (Thornthwaite and Kaser) and temperature-inversion

In this discussion of diurnal oscillation of velocity-profile one must presume gradient uniform wind for 24 hours (with unchanged isobar-pattern on the weather-map). Therefore, all the hourly wind-profiles will merge when extended upward indefinitely (neglecting radiation-heat-transfer effects). Correspondingly the barometric pressure-gradient in line of surface flow is assumed constant for the 24 hours. Level ground also must be assumed in order to neglect variable density-pressure gradients. With these limitations, the only hourly difference in shear-stress distribution vertically must be ascribed to possible change of momentum transfer downward from the faster overhead air.

Table 1--List of symbols

g (ft/sec^2)	Acceleration of gravity
ℓ (ft)	Mixing length (taken as 0.4z below 30 ft)
U (ft/sec)	Average wind-velocity at any height
z (ft)	Height above ground
θ (°R)	Potential temperature
ρ (lb.sec^2/ft^4)	Mass-density of air
τ_n (lb/ft^2)	Shear-stress under neutral conditions

The most striking evidence of increased transfer of momentum downward is the faster afternoon wind, which greatly exceeds the increase from neutral predicted by equation (1). That is, pouring heat into the bottom of the atmosphere supplies extra energy for turbulence but not as much as is indicated by the increased velocity. The explanation seems clearly to be in the extra coupling of air-layers by the transport due to vertical thermals. These thermals are so distributed [2] that only occasional instantaneous profiles show their presence. Over a considerable period, however, the extra momentum transfer by up-and-down air-currents serves to stiffen the profile [decrease (dU/dz)] above the knee of the curve. Thus actually in this region a daytime decrease in velocity-gradient indicates increased vertical transport, and only below the knee of the curve is the increased shear-stress seen in increased gradient.

Shear-stress distributions indicated for stable and for neutral thermal gradients--In estimating the shear-stress represented by observed profiles of velocity and temperature it is necessary to assume values for mixing length if the PRANDTL form of equation is used. The formulas we presented last year assumed that mixing length was a geometrical function and at a given level did not change from day to night. Continuing with this concept, the following development assumes for simplicity that $\ell = 0.4z$. Thus the shear-stress equation (applicable below 30 feet) is

$$|\tau/\rho| = 0.16\, z^2 \left[(dU/dz)^2 + (g/\theta)\,(d\theta/dz)\right] \qquad (2)$$

The use of this equation requires knowledge of temperature-distribution, which unfortunately was not observed for the velocity-profiles reported by THORNTHWAITE and KASER [3]. Observations of temperature-profile used in this example for buoyancy-stability are the averages from 02^h to 06^h recorded by KEPNER and BROOKS, January 3, 1942, at the Hurst Ranch, West Covina,

California. These are selected as the best (in our orchard-heating project) for over bare ground. Average wind-velocity of 1.40 feet per second was observed at 20 feet above ground for this period. For wind-velocities at other levels, it seems best to use the THORNTHWAITE-KASER observations for June 10, 1942, as a pattern because these also are for strong radiation cooling. (Aerological data and weather-maps kindly furnished by D. M. LITTLE at Dr. THORNTHWAITE'S suggestion show negligible change in overhead conditions from June 9 to 10. The barometric pressure fell two mb in 24 hours, but the pressure-gradient increased only from 1.72 to 1.84 mb per 100 miles, with slight change of direction from southwest to west-southwest.) The velocity averages for 03^h-07^h were taken for the stable condition. (The profile for 07^h-08^h is taken to represent the neutral condition, and the average of 11^h to 14^h for a typical superadiabatic condition.)

Transitions between turbulent and laminar flow--The change of shear-resistance in the alternating transition between turbulent and laminar flow is well described in PRANDTL-TIETJENS' [4] report of the COUETTE investigation. The investigation was of pipe-flow with the head of water so chosen that with laminar flow (low fluid-friction) the velocity increased to above the critical Reynolds number, whereupon the flow would become turbulent. Then with the high fluid-friction due to turbulent flow the velocity slowed to below the critical Reynolds number and laminar flow was again established. This automatic alternation in the nature of the flow was accompanied by cyclic variation in resistance-coefficient from 0.015 to 0.080 with corresponding velocity-range from 4.1 to 3.1. The resistance-coefficient in the transition-periods varied in accordance with the lengths of pipe occupied by each mode of flow.

Repetitive alternations between laminar- and turbulent-flow patterns have been observed also in the buffer-region near a pipe wall between the wholly laminar boundary-film (for smooth surfaces) and the wholly turbulent core. In this buffer-region the mean velocity-profile shows a smooth transition (without discontinuity in velocity-gradient) from laminar gradient to turbulent gradient. This is explainable by the proportion of time taken by the respective flow-types sweeping past a given station. Thus near the laminar film the nature of flow is predominantly laminar with occasional intrusions of turbulent flow, and the shear-resistance here only slightly greater than that corresponding to steady laminar flow. At the middle of the buffer-region the duration of occurrences of laminar flow would total half the time and the mean flow-resistance would be due half to laminar flow and half to turbulent flow; and so on across the buffer-layer until the occurrences of laminar flow-cells would be so seldom that the shear-resistance can be ascribed entirely to turbulent momentum exchange.

Detached laminar-flow parcels due to turbulence-suppression--In view of the known examples of mixed laminar and turbulent flow, the authors suggest that buoyancy-stability in free air can be so strong as to damp out turbulence [see equation (1)], perhaps as if by raising the critical Reynolds number locally. Then, of course, in the locale of laminar flow, since equation (1) would not apply, the velocity-gradient would increase greatly (due to reduced friction under constant streamline pressure-gradient). The locally-increased velocity-gradient affords momentarily increased available kinetic energy, thereby reestablishing turbulent flow. Thus throughout the entire region of strong buoyancy-stability there would be local transients alternating between laminar and turbulent flow. At any one instant the velocity-profile could never have the shape of the mean profile. Yet the mean profile would indicate the time-proportion of laminar and turbulent flow-resistances for a given shear-stress distribution.

The same reasoning could be applied in another way, visualizing a sharp reduction in scale of turbulence, involving distinctly different momentum transfer, such as is found at the edges of air-jets. Either interpretation, resulting in decreased shear-resistance, is in qualitative agreement with the reduction of mixing length suggested by ROSSBY and MONTGOMERY [5], but explainable in terms of known fluid-flow phenomena.

Another interesting implication of equation (1) is that, under typical radiation-cooling conditions, the kinetic term (with mixing length in the denominator) decreases with height more rapidly than the thermal term. This indicates that the region of suppressed turbulence will form first at a moderate height above ground.

Interpretation of typical velocity- and temperature-profiles--Table 2 gives the results of interpreting the velocity-profiles of Figure 1 with a temperature-profile considered most suitable for buoyancy-stability conditions. The nearly uniform distribution of shear-stress for the neutral condition can be ascribed either to the great height of the maximum velocity-plane (retaining the conduit-flow concept) or else to predominant momentum transfer downward from the overhead gradient-wind. Considering first that the shear-stress distribution is due wholly to barometric pressure-gradient (component in line of flow), this shear-stress distribution would be unchanged

Table 2--Ratios of night and day velocity-gradients and shear-stresses indicated for neutral and stable conditions near ground

Height above ground z	Ratio velocity-gradient to gradient in neutral atmosphere		Quotient of shear-stress and air-density, (τ/ρ)		Fraction of time during which suppressed flow must exist under buoyancy stability [a]
	Stable, $(d\theta/dz)>0$	Super-adiabatic $(d\theta/dz)<0$	Stable, $(d\theta/dz)>0$	Neutral, $(d\theta/dz)=0$	
(1)	(2)	(3)	(4)	(5)	(6)
ft					
28	1.14	(0.878)	0.85	0.30	0.65
24	1.18	0.912	0.89	0.30	0.66
20	1.19	1.00	0.89	0.30	0.66
16	1.15	1.08	0.80	0.31	0.61
12	1.11	1.17	0.60	0.31	0.48
10	1.08	1.22	0.53	0.30	0.43
8	1.025	1.29	0.40	0.28	0.30
6	0.850	1.31	0.30	0.32	...
4	0.625	1.25	0.19	0.41	...
2	0.451	1.75	0.075	0.32	...
1	0.336	2.21	0.025	0.19	...

[a] To match shear-stress found for neutral condition (assuming zero-resistance for suppressed flow).

from day to night. Thus the shear-stress calculated from the stable profile for wholly turbulent flow would be nearly three times too large at heights above 14 feet.

This suggests the existence of suppressed-turbulence air-parcels in sufficient frequency to reduce the shear-resistance by nearly two-thirds. In the last column of Table 2 is an estimate of the fraction of time during which the flow would have to be suppressed to reduce the effective shear-stress pattern to the values found for the neutral atmospheric condition. The ratio of the shear-stress quotients [neutral to stable, Col. (5)/Col. (4)] was taken at each level and subtracted from unity.

If there is appreciable extra momentum transport downward from the faster wind overhead, the turbulent shear-stress below 30 feet would be less than normal [Col. (5)] due to reduced coupling above 30 feet. Thus the reduction of the nocturnal turbulent shear-stress [Col. (4)] by parcels of suppressed flow would be even greater than listed in Column (6). The result of this semi-detachment would make the nocturnal ground-air flow responsive primarily to the surface stream-line pressure-gradient and especially sensitive to density-pressure stream-line gradients on sloped ground.

Possible laboratory verification of suppression of turbulence by buoyancy-stability--In experimental studies of heated horizontal jets, vertical traverses might be made from bottom to top, including turbulence-oscillograms. Observations of mean temperature- and velocity-profiles should indicate less gradient at the bottom edge, due to stability-resistance, until turbulence is suppressed. For the same air-velocity at the upper edge, there should be a steeper gradient characteristic of decreased friction in extra instability (due to heated air underlying the colder room-air). The oscillograms would reveal any alternating modes of flow, and whether the reduced resistance is due to laminar flow or to slow eddy-motion.

Conclusion--The existence of parcels of laminar flow or "slow-eddy" motion as a result of local suppression of turbulence by strong buoyancy-stability would decrease the shearing-resistance at moderate distances above ground. Interpretation of typical velocity- and temperature-profiles indicates such an effect noticeable from a height of six feet upward, and that a two-thirds decrease in shear-stress may occur above 14 feet. Accurate and simultaneous observations of velocity- and temperature-profiles are essential to further study of diurnal change of shear-stress.

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REPORT OF THE COMMITTEE ON EXTENDED FORECASTING

J. Namias

The first meeting of the Committee was held on June 14, 1944, with Lieutenant R. D. Elliott, Dr. H. W. Norton, Dr. H. C. Willett, and J. Namias (Chairman) present. Professor C.-G. Rossby, the other member of the Committee, was absent. It was suggested and voted that, in view of Professor Rossby's many activities, Major Wexler serve on the Committee as his alternate.

The functions of the Committee are:

(1) To keep abreast of developments in the field of extended forecasting (involving any period in excess of 48 hours).
(2) To furnish desired information to agencies or individuals concerning material or publications on extended forecasting and to expedite the preparation of bibliographies on the subject.
(3) To furnish opinions on various methods of long-range forecasting to reputable sources desiring such information. These opinions will be based as much as possible on a scientific evaluation of the technique, preferably through objective evaluation.
(4) To issue resolutions recommending that certain promising lines of attack on the problem of extended forecasting be encouraged.

The Committee will meet at least once a year and will also keep in contact through correspondence.

U. S. Weather Bureau,
Washington 25, D. C.

ON CLIMATIC ANOMALIES: ATMOSPHERIC-PRESSURE PROBLEMS

Henryk Arctowski

Climatology is a science of meteorological generalizations.

Monthly means of temperature and monthly totals of precipitation are most often the only data climatologists make use of in their studies. Evidently so-called "normal" means of long series of observations give the best maps of temperature- and rainfall-distribution and, eventually, of the range of variations. Atmospheric pressure is very seldom taken into consideration.

Some climatologists study climatic changes. They find questionable periodicities, correlations with sunspot-cycles, correlations of seasonal anomalies of far-distant stations, relations with sea-currents and polar-ice conditions, and perhaps also auroras, magnetic data, or anything that might change the price of corn, or epidemics and mortality.

It is most astonishing how few students of climatic variations have adopted synoptic methods, examining the changes of annual and monthly means the way meteorologists examine and compare the anomalies of weather. In such studies the changes of atmospheric-pressure distribution is the indispensable guide-line.

More than 40 years ago I compared the pressure-waves observed during the winter and the summer on board the Belgica in the Antarctic. I made the mistake of eliminating changes of less than five mm of amplitude. Several years later the same thing was done by SIMPSON and MEINARDUS and the comparison of data gave interesting results on the seasonal variation of the duration and the amplitudes of Antarctic pressure-waves and their mode of displacement, and the principal result of such comparisons was overlooked because of the "five-mm mistake."

The intercrossing of wave-motion was not discovered then and this problem is still to be solved because upper-air data are indispensable in order to know just why the frequency of pressure-waves on Kerguelen Island is more than twice the frequency of Antarctic waves. A comparison of barograms plainly shows most characteristic discontinuities. The appearance on both sides of a high (observed on the Gauss) in the Antarctic, of a jump down and a backing up of the mercury of less than five-mm difference, may correspond to a low of Kerguelen. Since such is often the case, no wonder that the number of waves, of at least five mm of amplitude, observed on Kerguelen Island, might have been the double of those observed simultaneously at the Gauss station. Maps of isallobars (and of isallobars traced for different atmospheric levels) change entirely the problem of atmospheric waves.

Absolutely the same applies to the annual variations due to the transport of air-masses from continental to oceanic "centers of action" of atmospheric circulation, and from the Northern Hemisphere to the Southern and back again, as well as to how the annual pressure-variations observed in some regions differ from what they should be if everything was simple and regular and if the distribution of land and water, acting upon the seasonal pressure-changes,was less irregular than it is.

The size and the shape of the continents regulate the amount of over-pressure observed during the cold months of the year. Take Barnaoul in central Siberia as an example. The curve of the monthly means of the years 1921-30 is asymmetric. The mean pressures for the months of September and October are apparently too high; this is more so in the case of Irkutsk. It is just as if two distinct annual variations, of different amplitudes, were superimposed--one belonging to the winter, the other to the summer months. From July to September, pressure increases more rapidly than it decreases from April to July. Drawing the curves year by year, a very characteristic deficit of pressure in December or January may be observed, except in 1925-26 when the winter maximum is well developed, although belonging to a downfall of the September-to-April curve.

Where can we expect to find the cause of the lack of perfect continentality of the most continental region of our Globe? Is it the Icelandic low that acts far into Siberia or is it the seasonal transport of air-masses from the Southern Hemisphere which is insufficient to feed, to fill-in the funnel of upper-air strata due to the extremely cold, contracted bottom air? Not much imagination is needed to see, a priori, that the total area of Australia, South Africa, and South America along the latitudes of the disrupted high-pressure ring of the Southern Hemisphere is insufficient to give up the necessary amount of air needed in central Asia for a full development of the winter maximum.

During September and October air-masses come in towards Barnaoul in quantities apparently greater than the demand dictated by the fall of temperature, but soon a reaction takes place--a transition to the winter deficit.

If you had the time to listen, I would compare the pressure-data of eastern Siberia with those of antipodal South America--a surplus on one side not compensated by the deficit on the other; a pull upon the axis of the Earth's rotation; the cause of the annual variation of latitude. The KIMURA term and the semi-annual variations of pressure should be carefully investigated. But the most interesting of all is the CHANDLER variation of latitude, of approximately 14-month duration. The CHANDLER period seems to vanish during certain series of years, then reappears anew, dominating the annual variation. It will interest you to know that the same applies to pressure-variations for a number of stations. Therefore, for consecutive years, January, March, and May will have corresponding maxima, modifying in turn differently any normal variation. Consequently, years that follow each other should not be alike. And, as to the cause of such an apparent chaos, better not speak about it, at least not for the present.

Planetary influences upon the Sun, solar-constant variations and atmospheric pressure, the Moon and atmospheric tides and weather-changes, are subjects which I have systematically studied during my last three years of research at the Smithsonian Institution. When I will be able to publish my report on all this work, I do not know, because the upper-air data so kindly put at my disposition by the Chief of the United States Weather Bureau, far from simplifying my task, made me travel up

into the ionosphere far above the highest meteorological soundings, and I found there a most unexpected relationship with the day-to-day barometric readings.

At the present time it seems to me that sudden or temporary changes of the quality of solar radiation, acting directly upon the highest levels of our atmosphere, must react indirectly upon atmospheric circulation and a polar overcharge of pressure, which is discharged by waves, by baroterons.

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Washington, D. C.

ERRORS IN THE SYNOPTIC WEATHER-CHARTS WHICH COVER THE GREENLAND REGION

William H. Hobbs and Ralph L. Belknap

Greenland is a very large island with the outline of a human left ear. Its length in a north-south direction is about 1,600 nautical or 1,800 English miles, and its average breadth about 600 nautical or 750 English miles. Its area is comparable roughly with that part of the United States which is east of the Mississippi River. Save for this elongated outline, Greenland's model is that of an old-fashioned hunting-case watch--it is a flattened dome with increasingly steep outward slopes upon its borders. With exception of a marginal ribbon of land usually less than 50 miles in width, Greenland is blanketed by a glacier which everywhere forms its surface (see Fig. 1).

Though the maximum elevation of this glacier-surface is usually given as around 10,000 feet, its altitude is actually unknown, for this assumed elevation is based on aneroid recordings made during transections. (Barometer-readings are determined largely by two factors, altitude and weather-condition, but the decrease in atmospheric pressure in penetration of the island has here been ascribed wholly to altitude. The centrifugally directed winds of Greenland indicate that the altitudes given by the maps are too low by many hundreds of feet. That this is so is further indicated by the failure of the meteorological pattern to accord with the assumed topographical one. Further evidence is possibly supplied by the crashes of Allied planes of the Ferry Command that had used the maps to determine safe flying-altitudes.) The Wegener Greenland Expedition of 1929-31 ran a line of precise levels from the west coast in latitude 71° to their station of Mid-Ice, but the result has not been published and still remains a German military secret.

The fixed glacial anticyclone which at all times overlies Greenland [see 1 of "References" at end of paper] is modeled on the form of an hour-glass, a model elsewhere realized on our planet only above the Antarctic glacier of the same continental blanketing type. The Antarctic anticyclone is, however, roughly centered near the South Pole, and cyclones circle about it in a direction from west to east in continuous procession within the zone of the "roaring forties" and the "screetching fifties and sixties" (of latitude).

Greenland is centered in an eccentric position (73° north) to the Earth's northern pole and the glacial anticyclone above it thus lies athwart the paths of the more northerly cyclones arriving from the southwest. The southerly cyclone tracks by-pass Cape Farewell at the southern tip of Greenland, and they continue eastward into the Icelandic Low or are deflected northeastward through the Greenland Sea.

All air-masses which arrive from western quarters and are able to advance into the Greenland Area are above the level of 3,000 meters where they make the transit of the west coast. (From balloon-observations made at the three stations of the University of Michigan located at Ivigtut in latitude 61°, at Mount Evans near latitude 67°, and at Peary Lodge near latitude 74°; see Reports of the Greenland Expeditions of the University of Michigan, v. 1 and v. 2.) When these currents had arrived about 25 English miles inland, where the glacier-surface was nearly 1,000 meters higher, this ceiling to the outward-blowing winds was found to be about 1,000 meters higher, or at the 4,000-meter level [2] (see Fig. 2).

As a result of coordinated observations by American, British, and German expeditions made in 1930-31 and in 1932-33, it has now been definitely determined that the cyclones which arrive at the Greenland west coast are halted there and pass up Davis Strait to be dissipated on reaching the Polar Basin, the oceanic area north of 80° north [3]. During these two periods 1930-31 and 1932-33 (Second International Polar Year), for the first times in history the number and reliability

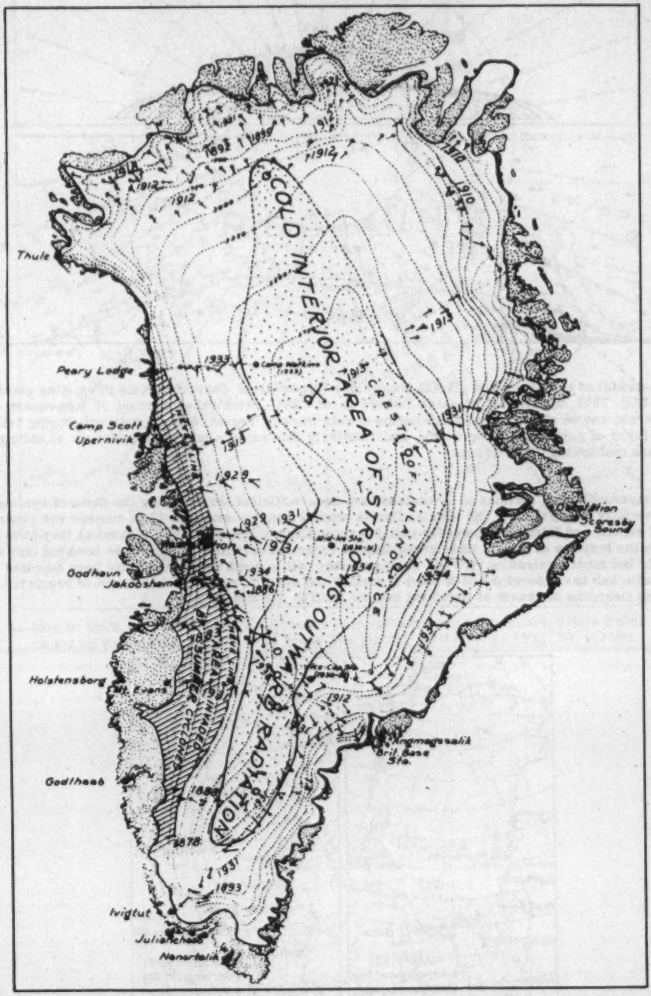

Fig. 1--Map of Greenland which sets forth topographical model on basis of aneroid readings, and the meteorological model of the fixed glacial anticyclone (Note the lack of accord)

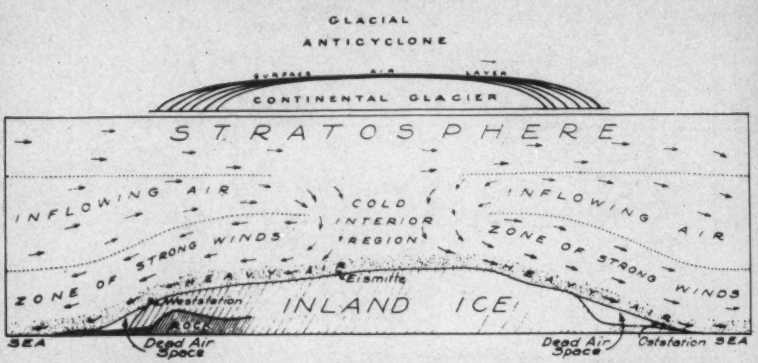

Fig. 2--Model of the Greenland glacial anticyclone (upper) from characteristics of existing glaciers (p.288), 1911, and model of same (lower) as of 1944, which takes account of subsequent research, and so shows sharp delimitation of cold interior region, definite outward sloping ceiling of layer of outward blowing winds, and relatively thin surface layer of heavier air at bottom of these outblowing air-currents

of the meteorological stations of Greenland have been sufficient for following the paths of cyclones in its vicinity (see Fig. 3). The official Danish coastal weather-stations, 12 in number and generally of second and third grade, supply reliable recordings of pressure, but, located as they have been in the bottoms of fjords, their recordings of force and direction of wind have been not only unreliable but most misleading [4]. Six of this number, all in south Greenland, have been supplied with radio and have therefore been used in making the synoptic weather-charts issued regularly by both the Deutsche Seewarte at Hamburg and the British Air Ministry.

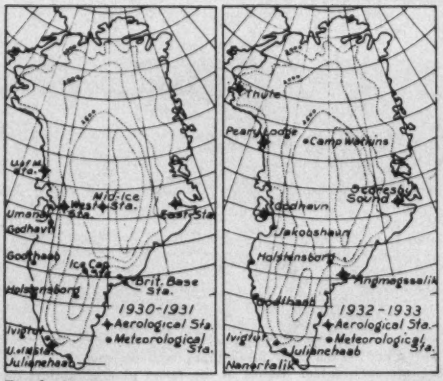

Fig. 3--Maps to show location of meteorological and aerological stations in Greenland in 1930-31 and in 1932-33

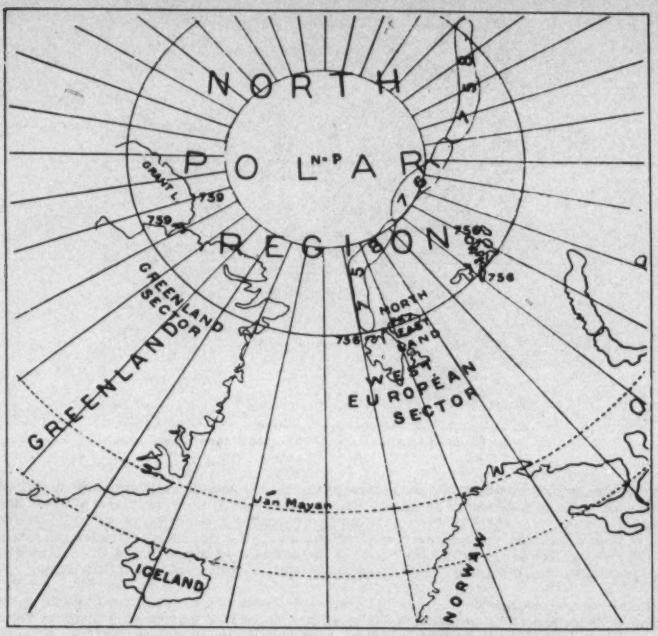

Fig. 4--Map to show average annual air-pressures in millimeters of mercury within Polar Basin, based on exploration before 1926, from The glacial anticyclones (Fig. 50, p.149)

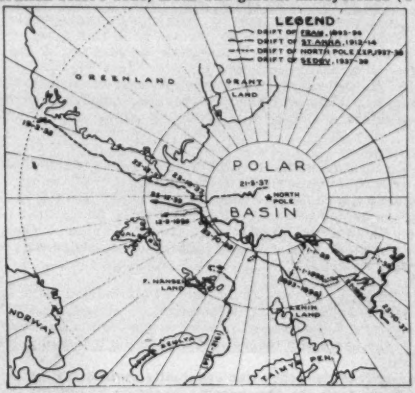

Fig. 5--Map of Polar Basin to show recent Soviet exploration

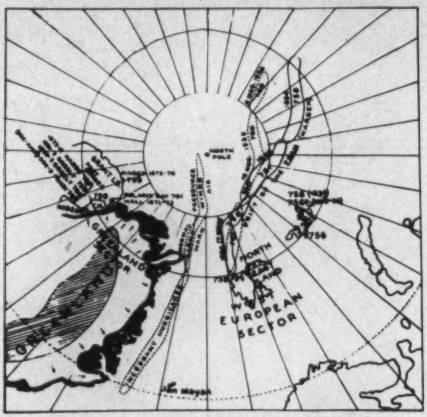

Fig. 6--Map to show meteorological conditions over Polar Basin

The inner core of the descending air-currents of the Greenland anticyclone is sharply delimited on all sides by a sudden rise in air-temperatures and by an equally sharp fall in daily temperature-range. The force of the centrifugally directed air-currents outside this central core varies between calms and winds of hurricane velocities (100 to 150 or more miles per hour). These fierce katabatic winds extend far out over the sea beyond the coasts of Greenland with the same general direction though with dextro-rotary deviation due to rotation of the Earth.

Official weather offices which issue daily synoptic charts inclusive of the Greenland Area (see, for example, those issued by the British Air Ministry), have long persisted in ignoring the above-described conditions, despite the fact that these have been known in greater part for a quarter of a century, and they continue to draw the isobars across Greenland exactly as though it were a quite normal expanse of sea. The North Polar Basin, the Arctic Ocean north of 80° north, has also been treated by them as though it were at all times an area of high atmospheric pressure and low air-temperatures. Yet, as long ago as 1926, the senior author of this paper showed on the basis of such exploration as had then been made that the Polar Basin appeared to be the unique large area of average normal atmospheric pressure upon our planet [5] (see Fig. 4) and that it is far from being an area of extreme cold. (In the summer the air-temperatures are often excessively warm, and in the winter much warmer than those over central Siberia or central British America. Then on the Arctic coasts, the air-temperature drops with southerly winds, and rises with wind from the Polar Basin.)

The recent Soviet exploration within the North Polar Basin (North Pole Station, May 21, 1937, to February 19, 1938; drift of the Sedov 1938 and 1939, and that of the Santa Anna in 1914) has confirmed and extended greatly the earlier evidence (see Fig. 5). The full meteorological report of this work will probably not be published until the termination of hostilities in Europe, but a summary has already been printed in the Russian language [6], and the pertinent part of this has been kindly translated for us by D. K. KAZARINOFF, Instructor in Mathematics at the University of Michigan. To quote from this report:

"The expedition of SS Sedov, as well as the North Pole Station, were functioning since the establishment of the present Russian network of meteorological stations. This circumstance has permitted the drawing of isobars, lines of equal pressure, for the Arctic Basin on the basis of actual observations, and not on the basis of a theoretical hypothesis that was in use before the year 1937. (Our italics.)

"In this regard the drift of the Sedov was especially instructive. For the period 1937-39, Figures 3, 4, 5, 6, and 7, set forth the atmospheric-pressure charts for the Arctic Basin for each season during that period. These charts were prepared by B. L. DZRDZEEVSKY, making use of

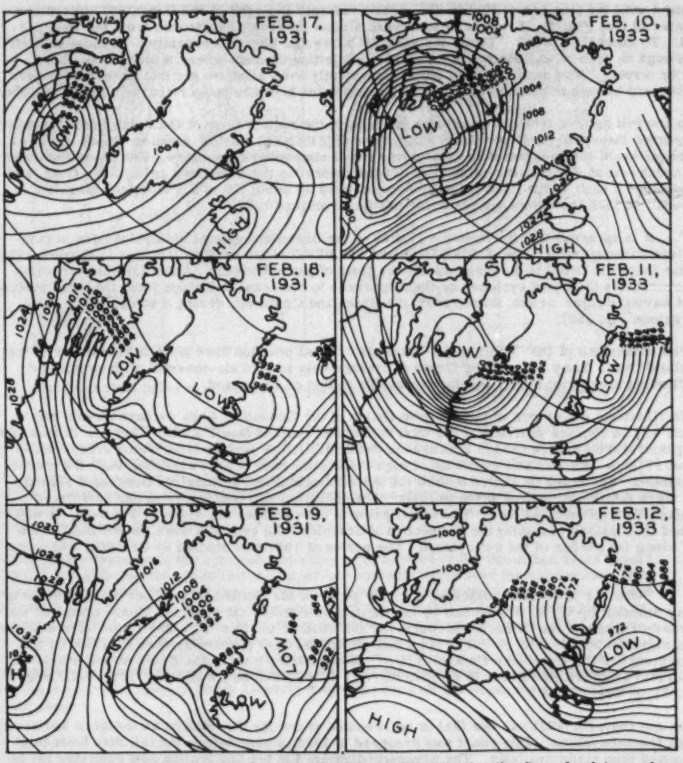

Fig. 7--Series of daily synoptic charts by British Air Ministry for the Greenland Area when cyclones approached west coast

the synoptic data from North Pole Station and Sedov.

"From these charts one sees how different the synoptic situation is for the different seasons. The usual hypothesis of a constant polar anticyclone breaks down in the light of the observations of the North Pole Station and Sedov. During the summer season, July and August, there is a region of lower pressure north of the nearer part of the Arctic region." (Italics in the original.)

The point of greatest interest in this summary statement is that in the chart to show mean annual air-pressure the isobar of 1013 mb surrounds the central Polar Basin, with no other isobar within it--hence the Polar Basin is a region of marked mean normal atmospheric pressure, exactly as was foreshadowed by the earlier and less complete data.

The popular narrative account of the drift of the North Pole Station [7] has offered further confirmation of this conclusion. To the north of 80° (May 21 to December 24, 1937) the wind-force varied from complete calm to occasional light winds, usually insufficient to turn the windmill used to charge the batteries. The air-temperatures were uncomfortably warm and accompanied by so much melting of the floe that beds and other furnishings had to be shored up. These conditions

continued until the floe had drifted to 80°, where suddenly the orbit of the Greenland anticyclone was entered (see Fig. 6). From here southward almost incessant hurricanes from the west prevailed. To quote PAPANIN: "Damn the wind! It blows and blows incessantly. We must be drifting through an area of endless winds. Greenland is letting us know where it stands" (p. 229). Later he wrote: "The wind has been blowing constantly ever since we got into Greenland waters. The blizzard has made hermits of us. We stay inside the tent like badgers in their lairs" (p. 236).

In the full light of this new knowledge concerning the meteorology of the Polar Basin the wholly unsupported theory of the Polar Basin anticyclone (BJERKNES) must be given up and be replaced by recognition of the fact that it is an area of normal atmospheric pressure. The so-called polar front northwest of Europe (the original one of the theory) is the Greenland anticyclone front, and this involves a shift of the fixed anticyclone southward by some 700 miles along the meridian of 40° west. In 1926 the senior author wrote in Glacial anticyclones:

> ". . it is apparent that the author's studies of the Greenland glacial anticyclone are in complete harmony with those of BJERKNES and SOLBERG of the cyclone families in Europe. The one theory is fitted to the other as are the teeth of geared wheels. Alone the cold air which rejuvenates the dying cyclones on their approach to the coast of Europe from the west, instead of having a polar origin, issues from the Greenland Continent, during a stroph of the anticyclone" (p. 155).

The extensions of the "polar front" from its original position have little in common with the Greenland front. They are shifting fronts of cyclogenesis to cold air-masses, with no similar fixed feeding area from higher levels comparable to that of Greenland.

To illustrate the errors of the synoptic charts of the Greenland Area we have chosen two periods when a cyclone approached the west coast of Greenland (see Fig. 7). They are in no sense exceptional and they were chosen because the dates fall within periods from which exceptionally full and reliable data are now available, though these were only in part available when the charts were issued. The maps of Figure 3 show the meteorological and aerological Greenland stations which were functioning during these periods. The operation is a post-mortem one performed long after the cyclones had died. The actual paths of the cyclones are given in Figure 8. It will be noted that instead of making the transection of Greenland the cyclones were switched up Davis Strait along the border of the anticyclone. The series of 1931 was studied by GEORGI, who wrote of it:

> "With the disposable material, i.e., the paper of Mr. MIRRLEES, observations placed at my disposal by W. H. HOBBS and by the Danish Meteorological Institute, I have compiled the weather maps of the Deutsche Seewarte for the weather periods. . . . The center of every low is signified by the date. . . . It is seen that the tracks have apparently been modified by the existence of the Greenland Continent . . . . the stationary lows of the Davis Strait, whose normal eastward movement is stopped there." [Greenland as a switch for cyclones, Geog. J., v. 31, p. 344, 1933.]

On the chart for 1931 one low (21) is represented at the Ice Cap Station as though it had really invaded the anticyclone. This chart was prepared in 1933, a year before the full data from that station had been made available. The pressure-diagram for Ice Cap Station now published [8] indicates no low-pressure area there on February 21 (see Fig. 9).

The cyclones of February, 1933, have been studied in the same manner by the junior author, who has written of them [9]:

> "From these [observations] for the month of February, 1933, the month having the largest number and the most severe of our storms, a chart was prepared (Fig. 6) showing the location of the center of each low-pressure area. This one was the method employed by GEORGI and the diagram thus prepared using the February data is another proof of his contention that Greenland acts as a 'switch for cyclones'. The chart shows the location of the centers from day to day, but more important here is the fact that of over 30 cyclones thus located only one may have crossed the ice-cap and that one in the southernmost part of Greenland. It also indicates that practically all the lows move up along either the west or the east coast; very often there are separate disturbances moving up each coast simultaneously.
>
> ". . This anticyclonic condition, the 'glacial anticyclone' of HOBBS, is the mechanism that really acts as the 'switch' described by GEORGI." [See also 10.]

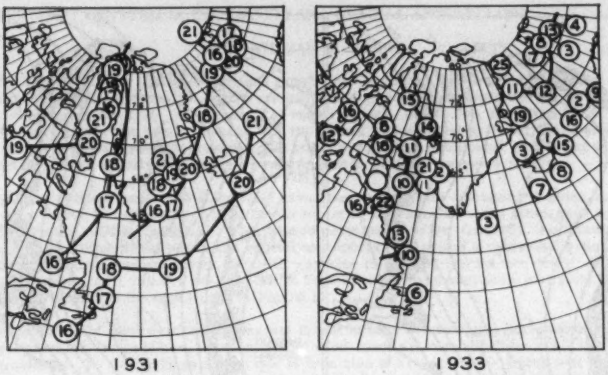

Fig. 8--Actual paths of cyclones represented on the synoptic charts of Figure 7

The junior author has prepared "post-mortem" synoptic weather-charts corresponding to the middle date in each of the series of Figure 9, but with use of the fuller data now available (see Fig. 10). It may be confidently asserted that all charts of the area must conform to this general pattern so far as Greenland itself is concerned. In the brief summer season strong cyclones from the west will impinge upon its western coast in some places through a marginal strip of as much as 100 miles, but in winter not at all. This has been proven by the German observations made at Weststation in latitude 71° [10].

What finally becomes of the cyclones when they have arrived at the Greenland West Coast? It is highly probable that they pass into the upper-air currents which feed the anticyclone. The junior author has shown (loc. cit.) that at his Peary Lodge Station on the Greenland West Coast in latitude 73°.5, the lows which approach from the west are accompanied by the same changes as those associated with a warm front. Most characteristic is the cloud-sequence. This is from cirrus through cirro-stratus, alto-stratus, stratus, and finally precipitation with nimbo-stratus. The warm front of the low thus appears to ride up over the outflowing air of the anticyclone so that much of its moisture is precipitated there as it goes into occlusion. A partial parallel may be seen on the Pacific Coast of North America where the lows off the ocean meet the coastal mountain ranges.

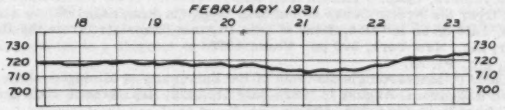

Fig. 9--Pressure-diagram for February dates in 1931 at Ice-Cap Station (after Mirrlees)

References

[1] WILLIAM H. HOBBS, The glacial anticyclone, the poles of the atmospheric circulation, with an introduction by HUGH ROBERT MILL, Macmillan, 198 pp., 1926.

[2] In latitude 71° north, compare R. HALZAPPEL, Wiss. Ergebn. Deutsch. Grönl.-Exped. A. Wegener 1929 u. 1930-31, v. 4, Part II, p. 248, 1935; also KURT WEGENER, ibid., v. 7, pp. 4-31, 1940.

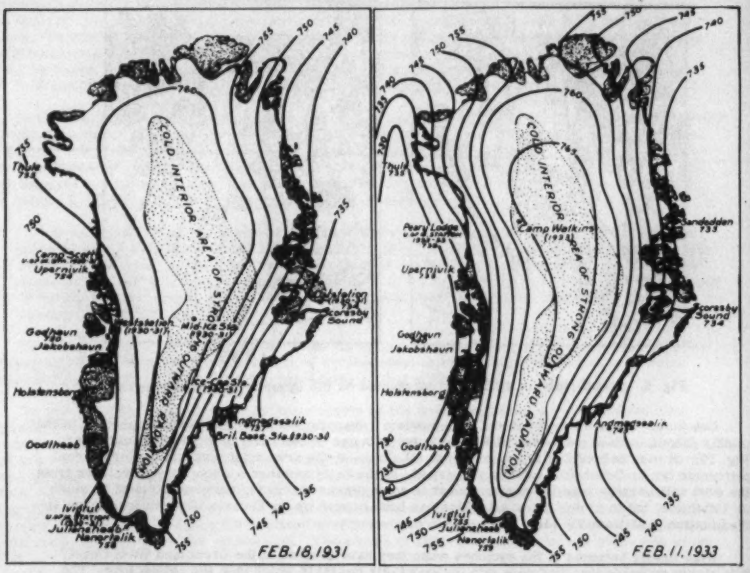

Fig. 10--"Post-mortem" weather charts of the Greenland Area for February 18, 1931, and February 11, 1933 (these should be compared with those of Figure 7)

[3] J. GEORGI, Greenland as a switch for cyclones, Geog. J., v. 31, p. 344, 1933; R. L. BELKNAP, Meteorological report of the University of Michigan—Pan American Airways Greenland Expedition, August 1, 1932—July 31, 1933, Rep. Greenl. Exped. Univ. Mich., Sci. Ser., v. 6, Part II, pp. 194-195, 1941; WILLIAM H. HOBBS, Nourishment of the Greenland Continental Glacier, J. Geol., v. 52, No. 2, pp. 73-83, 1944.
[4] See J. Geol., v. 52, pp. 74-75, 1944.
[5] The glacial anticyclones, Chap. 3 and 10, map on p. 149.
[6] K. S. BADIGIN, Over the Arctic Ocean on the ship Sedov (in Russian), 1940.
[7] IVAN PAPANIN, Life on an ice floe, diary of Ivan Papanin (translated from the Russian), Julian Messner, Inc., New York, 300 pp., illus., 1939.
[8] MIRRLEES, loc. cit., Pl. XI.
[9] RALPH L. BELKNAP, Meteorological report of the University of Michigan—Pan American Airways Greenland Expedition, August 1, 1932—July 31, 1933, Rep. Greenl. Exped. Univ. Mich., Sci. Ser., v. 6, Part II, pp. 194-195, 1941.
[10] WILLIAM H. HOBBS, J. Geol., v. 52, pp. 77-83, 1944.

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RHYTHM IN THE GREENLAND GLACIAL ANTICYCLONE

WILLIAM H. HOBBS

The German and the British Greenland expeditions of 1930-31 gave to the world the first continuous records of meteorological conditions within the cold interior region of the Greenland glacial anticyclone [see 1 of "References" at end of paper]. Of the two expeditions the former was much the more important, for the reason that its station was manned by experienced and very competent meteorologists who were provided with some aerological equipment, and it was in operation [2] continuously for slightly more than a year (August 1, 1930, to August 8, 1931).

The observations made at Mid-Ice have never been adequately discussed in print, for after the death of the leader in the winter of 1930 the direction of the expedition was taken over by the strong Hitler party-man, KURT WEGENER, who refused permission to Dr. GEORGI, the director of the station, to treat his observations in the expedition reports. By use of a remarkable meteorological diagram, of which no parallel exists, GEORGI was able to make it tell its own story. This diagram, four feet in length, on a smaller scale and with English names and additional marginal material, has been reproduced in the upper part of Figure 1.

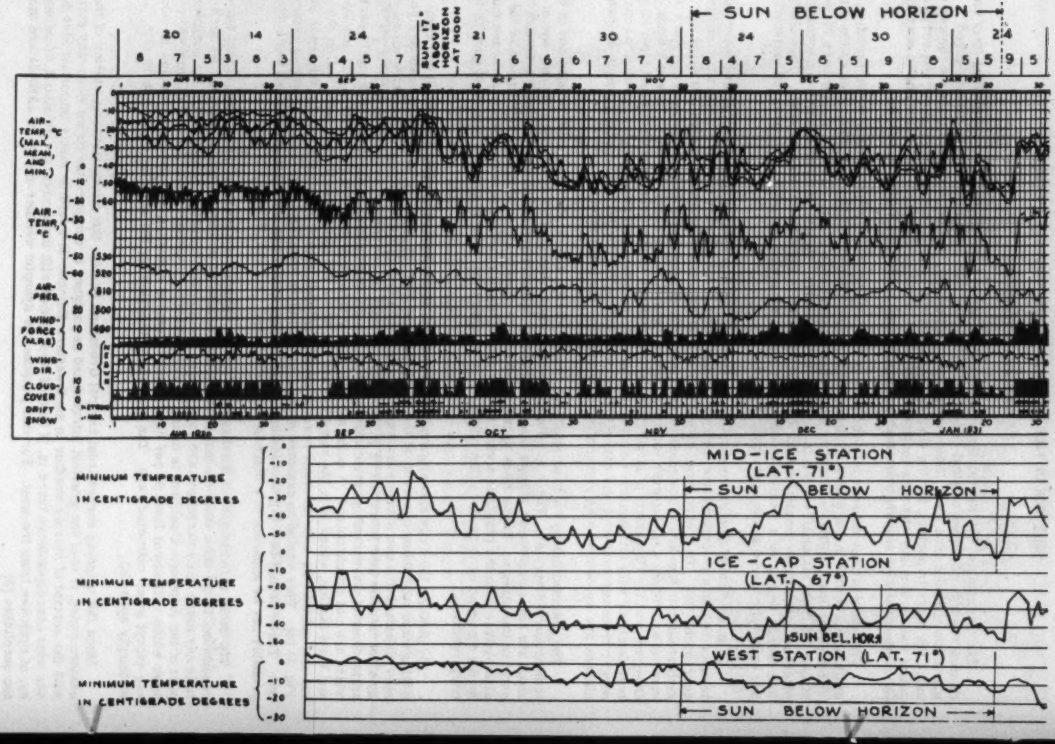
On inspection of this remarkable diagram it will at once become apparent that within the cold interior region air-temperature, nebulosity, and wind-force all vary together in the most striking correspondence. To a very large extent this is true also of air-pressure, which will surprise meteorologists who are accustomed to associate rise of pressure with fall of air-temperature and vice versa. There are, however, some exceptions shown in the chart--a notable one in March. Observers at the University of Michigan weather-stations on the Greenland west coast have long been familiar with this unusual relationship between pressure and temperature, for about as many surges from the interior come with rising as with falling barometer, and certain of each of these classes are associated with rising air temperatures--the foehn effect.

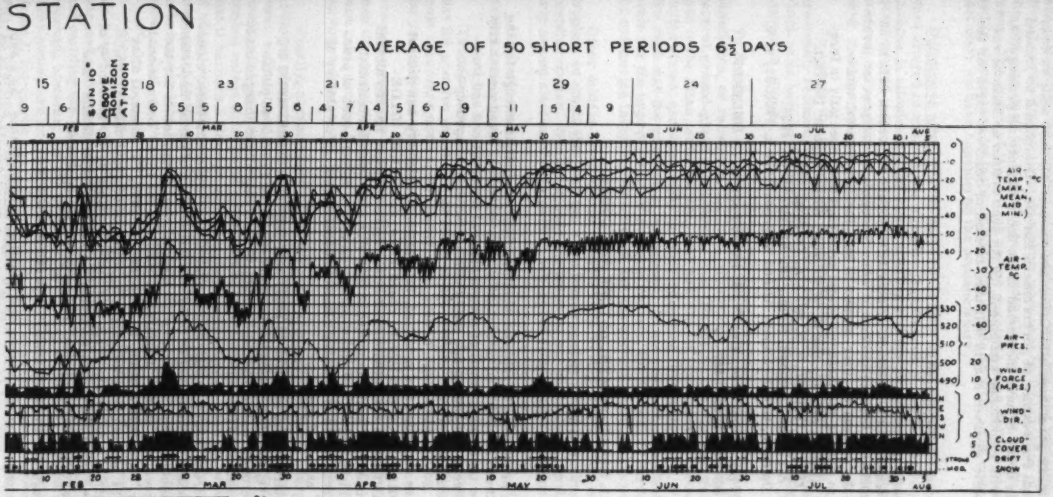
The diagram betrays also an approach to periodicity, a sort of rhythm best brought out in the temperature-diagrams. There is a longer period which averages 23 days, and a shorter one of about six and a half days. Making use of maxima of temperature, these periods have been indicated in the margin. These rises in temperature are closely associated with an increase of the cloud-cover with the response a very sudden one. Outgoing radiation is apparently screened out by the cover so as to produce this effect. It is so sharp that it is registered almost at once in the body-reaction.

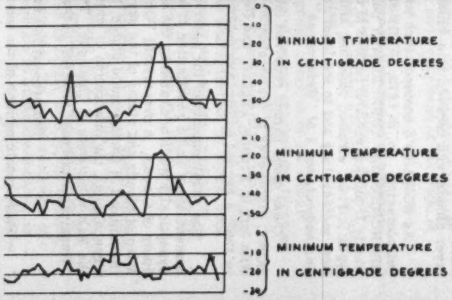
By plotting the daily air-temperatures recorded at the British Ice Cap Station [3] and comparing them with those observed on the same dates at Mid-Ice, exactly the same periods are observed, though the two stations are separated by more than 250 nautical, or 280 statute, miles and by 4° of latitude (see lower part Fig. 1). This can only be interpreted to indicate that the glacial anticyclone of Greenland operates very much as a unit, rather than in separated component parts which are not synchronized. A quite similar comparison made between the interior Mid-Ice Station and West Station, which is in the same latitude but some 200 odd miles farther west and on the ice-cap outside the interior zone, reveals closely related but not identical periods (see lower part Fig. 1) [4]. This was to be expected since all winds blow from the interior station to this exterior one. There should be a lag of some hours for related changes at the West Station, but these would probably not be apparent in a diagram of this scale.

The most reliable part of the diagrams for the purpose of revealing the rhythm is that corresponding to the time when the Sun is below the horizon or at a small angle above it. At such time any mere daily variations are very small, and no place upon our planet except the unexplored part of the Antarctic Continent is in any way comparable. The surface is formed of pure white snow which reflects at least 80 per cent of any incoming radiation, and the Sun is too low to send any except much refracted rays. The ends of the diagram for the summer months make this strikingly apparent.

Since the outgoing surges from central Greenland become the strong westerly storms of the eastern coast, it is of the greatest interest and importance to compare the times when they start with the arrival of stormy weather in northwestern Europe. It would be vastly important also to see what correspondence there is, if any, of these times with the arrival at Greenland, or passage by, of cyclones from the west. For this purpose the synoptic weather-charts of 1930-31 are much too unreliable [5].


MID - ICE
AVERAGE OF 16 LONG PERIODS 23 DAYS
SUN BELOW HORIZON
SUN 11° ABOVE HORIZON AT NOON
AIR-TEMP. °C (MAX., MEAN, AND MIN.)
AIR-TEMP. °C
AIR-PRES.
WIND-FORCE (M.R.B.)
WIND-DIR.
CLOUD-COVER DRIFT SNOW
AUG 1930
SEP
OCT
NOV
DEC
JAN 1931
MINIMUM TEMPERATURE IN CENTIGRADE DEGREES
MID-ICE STATION (LAT. 71°)
SUN BELOW HORIZON
ICE-CAP STATION (LAT. 67°)
SUN BEL. HORS
WEST STATION (LAT. 71°)
SUN BELOW HORIZON




MINIMUM TEMPERATURE IN CENTIGRADE DEGREES
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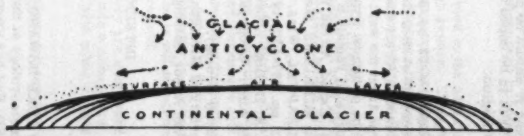

Fig. 1--Georgi's diagram of meteorological results at Mid-Ice Station, German Greenland Expedition of 1930-31

It is to be expected that one or more permanent mid-Greenland weather-stations will, as soon as is practicable, be set up to forecast the weather of northwestern Europe. One should be located in as high a latitude as practicable in order to have the period of the Sun's absence as prolonged as possible, and it should be provided with radiosonde equipment. When such station or stations are available, it is to be hoped that synoptic weather-charts will take account of observed facts for the Greenland Region.

References

[1] See J. Geol., v. 52, pp. 84-91, 1944.
[2] It has become evident that this station was maintained primarily to secure important data to be later used in forecasting the weather of Europe in time of war. Though a line of precise levels was run from the west coast to the central weather-station of Mid-Ice, the results, which would be of utmost importance in solving the meteorological problems and especially in forecasting, still remain a German military secret. See K. WEICKEN, Wiss. Ergebn. Deutsch. Grönl.-Exped. Alfred Wegener, 1929 u. 1930-31, v. 5, pp. 1-4, Leipzig, 1940.
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INTERNATIONAL CLOUD-NOMENCLATURE AND CODING

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History

Since LUKE HOWARD, in 1803, proposed a cloud-nomenclature that was simple enough for the needs of meteorology at that time, there has been an international nomenclature, based essentially on HOWARD, that has grown with the increasing detail of meteorological observations and forecasting. HOWARD distinguished between ice-clouds and liquid clouds, between heaped-up and layer clouds, and between rain-clouds and others.

As HOWARD'S nomenclature was expanded and modified, international diversity was natural yet confusing. So, in 1879, HILDEBRANDSSON published a cloud-atlas; and in 1887 HILDEBRANDSSON and ABERCROMBY published a classification of cloud-types they had chosen almost wholly from nomenclatures then in use. All were compounded of HOWARD'S four fundamental types (cirrus, stratus, cumulus, and nimbus). They chose them with an eye to the needs of practical meteorology and to the least disturbance of existing cloud-nomenclatures. [For history of this subject, see 1 of "References" at end of paper.]

These cloud names received international sanction in 1891, and, thanks to TIESSERENC DE BORT, discoverer of the stratosphere, the first international cloud-atlas, of 27 colored plates with text in French, English, and German, was published in 1896. Embodying slight changes made in 1905, a second edition was published in 1910.

The requirements of the polar-front theory and air-mass analysis for a more detailed cloud-nomenclature and a redefinition of some of the terms to bring out distinctions of prime importance synoptically were activated by the appointment, in 1921, of the International Commission for the Study of Clouds. A provisional "Observers' atlas" appeared in 1928 and the final "International atlas of clouds and states of the sky," abridged edition, in 1931, and, in 1932, "I: General atlas" (including 174 photographic plates, 31 of them colored), and "II: Atlas of tropical clouds" (in French only), the publication of which at a moderate price was made possible by the generosity of the Patxot Institute of Catalonia. The third and fourth volumes, "Atlas of special clouds" and "Physical processes involved in the formation of clouds" [2], have not yet appeared.

The present International Classification compared with the old

While retaining nine of the ten long-standard names, and adopting "nimbostratus" as a substitute for, but not the exact equivalent of, the ambiguous "nimbus", a more detailed nomenclature

was effected by the adoption of sub-genera, species, and varieties (see Tables 1, 2, and 3). The direct needs of synoptic meteorology were met by the adoption of a number-code of 27 states of the sky, nine each for high clouds, middle clouds, and low clouds and clouds of vertical development. The states of the sky for coding purposes were defined according to cloud-forms present, and in many cases by their amounts and trends as well. The code will be discussed in some detail after we have considered the nomenclature.

Definitions altered--The meaning of four of the nine cloud-names retained in the Atlas of 1932 were altered to enhance the synoptic significance of the distinctions between genera. Though the changes in altostratus and cumulonimbus and the abandonment of nimbus were criticized by W. J. HUMPHREYS before the Section of Meteorology of the Union in 1931 [3], criticisms that were considered, but not adopted, by the Cloud Committee for the final atlas, they deserve further discussion here, looking toward revisions after the war.

To assure the application of "cirrocumulus" to high, lumpy, or undulated clouds alone, as previously recommended in the United States [4], the new definition insists that not only do the cloud-units have to be small and without shading but also they must be associated with a small amount of cirrus.

To distinguish unfailingly the middle-height, moderately-dense cloud of falling ice-crystals, snowflakes, or raindrops, the term altostratus has been restricted to fibrous or striated clouds of general ground-glass appearance. Non-fibrous or non-striated ground-glass clouds are left nameless in the Atlas; nevertheless, they are almost invariably recorded as altostratus throughout the United States, and apparently in other countries (for example, S. PAPETTI recently told the author that such was the practice in Argentina). In the code, which embodies the changes in nomenclature made for the improvement of synoptic reports, the fibrous or striated nature is not mentioned for the categories including altostratus, but the ground-glass appearance is stressed.

Other middle-level, dense, sheet-clouds having sharp relief because they are composed of fine droplets so small that they fall at an inappreciable speed, have been made into a sub-genus, altocumulus opacus. Similar clouds not dense or not continuous are thrown in with other clouds formerly named altocumulus as part of sub-genus altocumulus translucidus.

Similarly, undulated or marked low clouds are now classed with stratocumulus instead of stratus (compare cirrocumulus for undulated high clouds).

The new term, nimbostratus, takes care of all sheets of falling snow or rain of such density that the position of the Sun or Moon is not visible through it. "Nimbus" was abandoned because most observers used it invariably when rain or snow were falling, and regardless of the form of the precipitating cloud.

Stratocumulus is now arbitrarily distinguished from altocumulus on a criterion of apparent size that is related to height. When the smallest of the regularly arranged elements of a cloud-bank (not counting the pieces on the margins) are more than ten solar diameters [about 5°] in their narrower dimensions, the cloud-system is to be called stratocumulus.

Finally, cumulonimbus is arbitrarily distinguished from overgrown cumulus by the simple criterion of whether or not the cloud shows cirriform or hazy signs of having reached the freezing-level, a distinction that usually marks the beginning of a thunder-storm. Unfortunately, this distinction is then thrown away: (a) By permitting a wholly cumuliform cloud to be called cumulonimbus calvus if it can be presumed to have freezing inside it already in progress from the fact that it harbors a thunder-storm or discharges a good shower, or is characterized by virga, none of which, according to the BERGERON-FINDEISEN theory, could occur without ice-crystals to start precipitation; or (b) when the top is not visible but the presence of a huge cloud with icy top is to be surmised from the occurrence of a thunder-storm, a darkening of the sky and a good shower, hail, or a menacing cloud with mammatus and virga.

Abbreviations--The improvement in the new Atlas of leaving hyphens out of abbreviations, a practice previously adopted by the United States Weather Bureau, was carried still farther by international agreement soon after, by reducing the three or four letters to two in each abbreviation and omitting the period. The ultimate in brevity, convenience, and unambiguity has not yet been reached, however, for the primary forms may as well be designated by single letters, as, indeed, their names are in the combinations; thus, C for cirrus and S for stratus. To avoid confusion between C for cirrus and C for cumulus, K for cumulus seems appropriate in all abbreviations, as was the practice in the United States Signal Service (Weather Bureau) in the 1880's [5] and at Blue

Hill Meteorological Observatory for nearly 50 years. A further improvement also formerly in the United States Signal Service practice and long in use at Blue Hill, deriving from the use of single letters for each primary form, would be to use only capitals, as clearer and more obvious, also as giving no chance for confusion of abbreviations with ordinary words, such as "AS" for alto-stratus not being confused with the word "As" at the beginning of a sentence.

Furthermore, the use of capitals for the genera would distinguish their abbreviations more clearly from those of the sub-genera, species, and varieties, now all in small letters. Indeed, the sub-genera, species, and varieties could be satisfactorily designated by single small letters, at a saving of time and space--usually the first letter of each name, but in cases of duplication some other suggestive letter, as "q" for cumulogenitus, "x" for nebulosus, "e" for vesperalis, "g" for congestus, "b" (bald) for calvus, "s" (smoke) for fumulus, "k" for cumuliformis, "w" (waved) for undulatus.

The present nomenclature: Families, genera, species, varieties

The nomenclature, being to provide names for the different aspects of clouds, must separate: (a) Clouds definitely of ice from those that are definitely of finely divided water; (b) convectional from non-convectional clouds; (c) clouds that are falling down from those that are not; and (d) clouds that are high versus middle versus low.

(a) Ice clouds versus clouds of minute droplets--Any clouds that exhibit halo-phenomena are definitely of ice; but clouds having a fine, fibrous quality or a hazy aspect, the pattern of which changes but slowly, may be safely assumed to be of ice. The clouds of such aspect are cirrus, cirrostratus, cirrocumulus, most altostratus, and some nimbostratus. Clouds that exhibit diffraction-phenomena, coronas or iridescence, are definitely of finely divided water; but a cloud with a sharp outline or markings other than fibrous may also be assumed to be of minute droplets. Such clouds are altocumulus, stratocumulus, stratus, cumulus, and cumulonimbus.

(b) Convectional versus non-convectional clouds--Clouds having knobby upper surfaces, except in a strong wind over rough terrain, are definitely convectional, active convection being in progress. Cirrus floccus, densus, and nothus, rounded cirrocumulus, altocumulus, and stratocumulus, cumulus, and cumulonimbus are of this type. Cirrus uncinus, some cirrostratus, altostratus, and nimbostratus, also some altocumulus, stratocumulus, and even stratus are derived from convective processes. Convective clouds flatten into sheets on reaching an inversion of temperature. Sheet-clouds formed from general upglide or lenticular or undulated clouds formed by localized ascent will, if the atmosphere is conditionally unstable, develop convectional aspects.

(c) Clouds that are falling down, being composed of ice crystals or raindrops of a size sufficient to give them an appreciable fall-velocity, are cirrus, cirrostratus, altostratus, nimbostratus, and cumulonimbus. Those that are not, are cirrocumulus, altocumulus, stratocumulus, stratus, and cumulus.

(d) The determination of height from cloud-form, a prime feature of the nomenclature, is based (1) on indications of temperature, as ice versus water, (2) on density, high clouds being generally less dense than low ones, owing to the smaller concentration of vapor at the low temperatures, and (3) on the apparent size of the units, the high cloud-units looking smaller than those of middle clouds and middle cloud-units smaller than the units of low clouds. This surmising of general height from cloud-form is of direct value in local and synoptic forecasting, for not only is the height at which condensation or other processes are revealed by the presence of clouds of direct importance, but also the height permits the translation of apparent cloud-speeds into rough actual speeds.

Families and genera--So the first grouping of the cloud-forms is by four families or height (high, middle, and low) and of vertical development. The high clouds are all cirriforms (genera Ci, Cs, Cc); the middle clouds are the two altoforms (genera As and Ac); the low ones are the low stratiforms (genera Sc, St, Ns); and the clouds of vertical development are the cumuliforms (genera Cu and Cb). (See Table 1.)

Sub-genera, species--The division into ten genera, four sub-genera, and eleven species presents the distinctions in quality, density, and apparent size between the lumpy cumuliforms, the sheet-like stratiforms, and the striated, hazy and mottled, or blank masses of falling ice-crystals, or snowflakes, or rain, that may appropriately be called "virgaforms", and their combinations; thereby indicating, after a fashion, the processes going on, and the heights. (See Table 2.) Additional species may be used.

Table 1--The International cloud-families and genera

Family	Genus	Abb.	By whom	When	Essentials in brief
High clouds	Cirrus	Ci	Howard	1803	Fibrous or silky; elements not merging into sheet
	Cirrocumulus	Cc	Howard Renou	1803 1855	Thin, small lumps or waves associated with Ci or Cs
	Cirrostratus	Cs	Howard Renou	1803 1855	Thin, fibrous, or milky sheet presumed to be of ice-particles by fibrous quality or halo-phenomena
Middle clouds	Altocumulus	Ac	Renou	1870	Patches or sheet with waves, lumps, rolls, or other non-fibrous markings; elements <5° across
	Altostratus	As	Renou	1877	Medium-dense fibrous or hazy sheet having aspect of ground-glass
Low clouds	Stratocumulus	Sc	Kaemtz	1841	Patches or sheet with waves, lumps, rolls, or other non-fibrous markings; elements >5° wide
	Stratus	St	Howard Hildebrandsson and Abercromby	1803 1887	Low, smooth, dry, or drizzly sheet; usually with variations in light
	Nimbostratus	Ns	Comm. Etude Nuages	1930	Blank or ragged wall or close-in of falling precipitation at, near, or above station
Clouds of vertical development	Cumulus	Cu	Howard	1803	Isolated, wool-pack clouds, almost invariably with horizontal bases
	Cumulonimbus	Cb	Weilbach	1880	Great snow-topped mass

Varieties, sub-varieties, casual varieties--The addition of six principal varieties, three sub-varieties, and four casual varieties adds helpful detail as to characteristics, which, for the most part, can be physically interpreted (see Table 3). Other varieties may be added as needed.

Critique of the definitions of genera--In the Atlas the genera are defined and then their characteristics are amplified under "Explanatory remarks" and "Species" On reading these one discovers that in several cases the definitions are not fully in line with the remarks. Thus Ci is defined as "without shading" yet there are species, Ci den and Ci not, that have shadows. The definition thus needs "usually" before "without shading" Cs "gives rise to halos", but since this is not invariably the case, here again "usually" should be inserted.

In the definitions of Ac and Sc there is no mention of the continuous sheet, thick or thin, wi. non-fibrous irregularities of surface of small or medium size, formerly As and St, respectively; nor is there mention of the definite criterion of what is "medium" versus "large" size, namely, that the smallest regularly arranged units or markings (away from the margin of the sheet) must be respectively less or more than ten solar diameters (5°) in their smallest dimensions.

The definition of St might be improved by mention of its soft appearance but varying density. The definition of Cu should begin "Dense clouds with vertical development . . ." rather than "Thick clouds . . .", a modification already made by the United States Weather Bureau [6]. Cb now specified as "the upper parts having a fibrous texture . . ." should, if Cb cal is retained, be changed to "the upper parts being icy is almost invariably revealed as such by a fibrous texture."

Table 2--The International cloud sub-genera and species

Name	Abb.	By whom	When	Genera Usually with	Genera Occas. with	Essentials in brief
			Sub-genera			
Translucidus	tra	Comn. Etude Nuages	1930	Ac	. .	Broken or thin in spots; Sun visible
				As	. .	Translucent; Sun visible through all parts
				Sc	. .	Broken or thin in spots; Sun visible
				St	. .	Ditto
Opacus	op	Comn. Etude Nuages	1930	Ac	. .	Continuous and rather uniformly dark
				As	. .	Dense; Sun not visible through some parts
				Sc	. .	Continuous and rather uniformly dark
				St	. .	Ditto
Praecipitans	prae	Ley	1894	As	. .	Precipitating or with marked virga
					Sc	Ditto
					Cu	Ditto
Fracto-	Fs	Poey	1863	St	. .	Broken
	Fc	Poey	"	Cu	. .	Frayed
			Species			
Filosus	fil	Clayton	1896	Ci	. .	Filaments (usually derived from uncinus)
				Cs	. .	Fibrous
Uncinus	unc	Maze	1889	Ci	. .	Hooked or tufted tops (usually derived from floccus or densus)
Densus	den	Besson	1921	Ci	. .	Dense (often usually derived from nothus)
Nothus	not	Comn. Etude Nuages	1926	Ci	. .	Cirriform top remains of Cb
Nebulosus	neb	Clayden	1905	Cs	. .	Thin and smooth or hazy veil
Cumulogenitus	cug	Comn. Etude Nuages	1926	Ac	. .	Spread from flattening Cu
				Sc	. .	Ditto
Vesperalis	vesp	Besson	1921	Ac	. .	Same as cug except usually an evening type
				Sc	. .	Ditto
Humilis	hum	Vincent	1907	Cu	. .	Small or weak, without cauliflower-top
Congestus	con	Maze	1889	Cu	. .	Large, with cauliflower-top (develops from hum)
Calvus	cal	Comn. Etude Nuages	1926	Cb	. .	Large thunderstorm or shower-cloud without cirriform top (develops from con)
Capillatus	cap	Comn. Etude Nuages	1926	Cb	. .	Cb with cirriform top (develops from con)

Perhaps it is too much to expect that the definitions of the genera could be made completely inclusive and exclusive, without overloading them unduly. Whether or not they are, the essential characteristics of the genera should be put into a table showing density (thin, medium, dense), extent of general units (detached, patches, sheet), size of minor units (fine, $<5°$, $>5°$), and details of appearance (fibrous, blank or hazy, flocculent, rolled or undulated, round-topped, down-bulged, ragged) [compare Tabular guide to cloud identification (for Atlas of 1910) in 4]. Opposite each item under each genus there should be entered one of the following four characterizations: "must be"; "usually"; "may be"; "can't be".

Table 3--The international cloud-varieties

Name	Abbr.	By whom	When	Genera		Essentials in brief
				Usually with	Occas. with	
Principal varieties						
Fumulus	fum	Ritter	1880	Ci	. .	Hazy spots
				Cu	. .	Hazy spots
					Ac	Hazy spots
					Sc	Hazy spots
					St	Hazy spots
Lenticularis	lent	Ley	1894	Ac	. .	Lens-shaped
					Cc	Lens-shaped
					Cs	Lens-shaped
					Sc	Lens-shaped
					St	Lens-shaped
Cumuliformis	cuf	Int. cloud atlas	1896	Ci	. .	Rounded top (see sub-varieties, below)
				Ac	. .	Ditto
				Sc	. .	Ditto
					Cc	Ditto
Mammatus	mam	Ley	1894	Sc	. .	Rounded downward
				Cb	. .	Rounded downward
					Ci	Rounded downward
					Ac	Rounded downward
					As	Rounded downward
					St	Rounded downward
					Ns	Rounded downward
Undulatus	und	Clayton	1896	Cc	. .	Waved, or in evenly spaced parallel lines
				Ac	. .	Ditto
				Sc	. .	Ditto
					As	Waved
					St	Waved
					Cu	In evenly spaced parallel lines
Radiatus	rad	Comn. Etude Nuages	1926	Ci	. .	Parallel lines apparently radiating from a point on the horizon
				Cs	. .	Ditto
				Ac	. .	Ditto
				Sc	. .	Ditto
					Cu	Ditto
Sub-varieties of Cumuliformis						
Castellatus	cast	Ley	1894	Ac	. .	Tall masses rising from connected bases
				Sc	. .	Ditto
Floccus	floc	Vincent	1903	Ci	. .	Separated, rounded-top masses of appreciable vertical development; ragged bases
				Ac	. .	Ditto
				Sc	. .	Ditto
Sub-variety of Undulatus and Radiatus						
Vertebratus	vert			Ci	. .	Regularly spaced units along a central line
Casual varieties						
Virga	virga			Ac	. .	Trails or smudges of ice-crystals or raindrops not reaching the ground; usually coarser than Ci
					Cc	Ditto
					As	Ditto
					Sc	Ditto
					Cu	Ditto
					Cb	Ditto
Pileus	pil			Cu	. .	Cap, hood, or scarf clouds just above, on or about the top of a cumuliform column
				Cb	. .	Ditto
					Ac	Ditto
					Sc	Ditto
Incus	inc			Cb	. .	Anvil-shaped cirriform top
Arcus	arc			Cb	. .	Arched roll cloud on squall front

A guide to cloud-nomenclature, on the organization-chart principle, that goes down to species and varieties and provides observers with tight alternatives to reach the proper name by following down through, is essential for all but long-experienced observers. One such, as well as the above-mentioned tabular guide, should be included in the next edition of the cloud-atlas. Both have recently been prepared by the author, for early issue with amplifying notes to observers by the United States Weather Bureau.

General critique--Notwithstanding the criticisms just mentioned, we must not lose sight of the important feature of the present classification, namely, its definiteness and the logical grouping of related forms, even though some forms in the grouping depart in some respects from the literal meaning of the names. The cloud-names as now defined seem to be about as close to a classification of clouds according to processes involved as a classification that must depend on cloud-appearance will permit. It is the International classification of today, which all nations have agreed to use.

Changes that seem desirable--It is inevitable that after a dozen years of use certain improvements can be made in the present nomenclature. The Cloud Commission expressly provided for addition of species and varieties. Cs den is needed for merging Ci den, and Ci and Cs virga for thin snowy trails, smudges, or sheets that reach down to or start from middle levels. Ac duplicatus describes a well-known aspect of the sky. As pallius is needed for the non-fibrous sheet of ground-glass aspect in contrast with the striated or fibrous sheet, which should be named As virgaformis. Altonimbus, a new genus, is required to designate the middle-level sheet of falling ice crystals or rain that blots out the Sun yet is not an immediate threat of precipitation. This term was used effectively at Blue Hill Meteorological Observatory for several decades. Such a sheet is now called Ns, yet Ns is defined as a low cloud. Retain Ns for the low, or immediately approaching, or enveloping sheet of falling rain or snow.

Cc, Ac, and Sc should not include non-cumuliform clouds--It seems to have been unnecessary for synoptic purposes and a confusing mistake to throw all marked sheet-clouds--high, middle, and low--out of the "stratus" category into the "cumulus". With the detailed terminology now sanctioned it is just as definite to name these sheets as species and varieties of Cs, As, and St as of Cc, Ac, and Sc. It is true that in weather-messages containing a single code-number for cloud-forms the separation of the present classification would not be obtained; but such messages are so inadequate and the use of the three-number CL, CM, and CH code is so universal that this consideration seems but a minor one. It is almost axiomatic that the terms "cumulus" or "cumulo-" should not be applied to any clouds without features at least somewhat cumuliform. So we should have Cs, As (op or tra), and St, und, mam, or lent, for non-cumuliform sheet-clouds or patches. Of these varieties, und or mam might occasionally be applicable to As op or tra virgaformis or pallius, but the species virgaformis and pallius would always separate these sheets of falling ice or water from those of fine droplets.

The problem of Cb--Since weather-messages tell of the occurrence of thunder-storms or showers, it seems that to retain these as identification-marks of Cb is in the same category as the use of the former "nimbus" for any rain-cloud. Reports on kinds of clouds visible should be what can be seen, not what is wholly surmised. So it seems proper to suggest that the separation of Cb into species cal and cap be abandoned and that Cb be reported only when the upper, snowy part is visible. When a thunder-storm comes over a station, the Cb would thus give way to Sc and then Ns.

The International cloud-code, CL, CM, CH

The codes for reporting the states of the sky with respect to clouds are defined in terms of the cloud-nomenclature already discussed. The main divisions of the code into three groups of nine numbers each are according to general criteria of height or vertical development as indicated by the cloud-form. So the CH-group deals with the high clouds family, of genera Ci, Cc, and Cs whether or not they are truly above 6,000 meters, the normal lower limit for such clouds. The CM-group is for the middle clouds As and Ac, also Ns and high Sc, clouds normally at heights between 2,000 and 6,000 meters, although the Ns usually reaches down to the ground. The CL-group includes the remainder of the family of "low" clouds, Sc and St, and clouds of vertical development, Cu and Cb, even though these last two often rise to middle and Cb usually to high cloud-levels.

The crowding of two families of clouds, one of which goes through all levels into one code-group, called "low" has proven very unsatisfactory because it leaves insufficient opportunity for expressing important differences in low-cloud conditions. The cure is, of course, the addition of another set of nine numbers to the cloud-code, which, after the vertical development of the family

for this group, can be designated as CV. The value of cloud-reports is such that it is not asking too much to accord four places in synoptic reports for them.

Suggestions for revised CH-, CM-, and CL- and added CV-code groups--The addition of a CV-group would permit taking the clouds of vertical development, Ac cast or floc out of the CM-group, thereby permitting a spreading of the five types now in CM7 over the numbers CM7-CM9. The relief of CL would also permit the removal of low Ns from the CM-code. The changes in code suggested, including changes in nomenclature already presented, are as follows:

CH1 to CH8 as now, CH9 to include Cs und and/or lent as well as Cc
CM1 As tra virgaformis or pallius (same as now)
CM2 As op virgaformis or pallius, or altonimbus (same as now, except low Ns omitted)
CM3 As tra und, or Ac tra (stable layer, same as now)
CM4 As tra lent or Ac tra lent or other small isolated patches of either (same as now)
CM5 As tra und or Ac tra advancing over sky (same as now)
CM6 As tra mam or op cug or Ac tra or op cug (same as now)
CM7 As virgaformis or pallius and other As or Ac in same cloud (in present CM7)
CM8 As virgaformis or pallius and other As or Ac in separate cloud(s) (present CM7)
CM9 Ac dup or op that is not cug (present CM7)
CL1 Fs, fair weather (present CL5)
CL2 Fs, bad weather (present CL6)
CL3 St tra (present CL5)
CL4 St op (present CL5)
CL5 Sc tra (present CL5)
CL6 Sc op (present CL5)
CL7 Sc cug or vesp (present CL4)
CL8 Sc prae or Ns (present CL5 or CM2, respectively)
CL9 Two or more levels of Fs or St and Sc or Fs or St and St (present CL5)
CV1 Fc alone, or with Cu hum, but predominant (present CL1 or CL6)
CV2 Cu hum alone, or with Fc, but predominant (present CL1)
CV3 Cu con present but no clouds lower and no Cb (present CL2)
CV4 Cb present but no clouds lower (present CL3)
CV5 Cu con or Cb present and other clouds below (present CL9)
CV6 Cu con or Cb penetrating preexisting Sc (present CL8)
CV7 Sc or Ac cast or floc without cauliflower-top (present CL5 or CM8 or CM9)
CV8 Sc or Ac cast or floc with cauliflower-top (present CL2 or CM8 or CM9)
CV9 Cb cast (upper Cb, that is, not due to convection from the Earth's surface (present CL3 or CL9)

Suggestions for new code on basis of form, amount, density, and change only to be accompanied by estimated or determined heights and directions and velocities of motion of tops and bases, seem to be in order, because the present code has the very serious failing that it is based on heights as surmised from form and not on heights determined or even estimated more closely than the three zones of height would give it. Also, the new code would provide for the direction and speed of each cloud-system. A complete report for each layer would require 13 digits, however; this should not be too much for the value presented.

First digit--Form: 1, fumulus; 2, Cu hum; 3, Cu con; 4, St, As other than virga or pallius, or Cs lent, und, or mam; 5, Sc, Ac, or Cc; 6, Ci; 7, Ns, As virga or pallius, or Cs fil or neb; 8, Cu prae; 9, Cb.

Second digit--Amount of sky-cover observed or surmised (present International code).

Third digit--Change in amount and/or density: 1, thin decreasing; 2, medium decreasing; 3, dense decreasing; 4, thin increasing; 5, medium increasing; 6, dense increasing; 7, thin advancing from beyond horizon; 8, medium advancing; 9, dense advancing.

Fourth to eighth digits--Height (2); direction (2); and velocity (1) of cloud-base.

Ninth to thirteenth digits--Same, for cloud-top.

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RAINFALL-MEASUREMENT AS INFLUENCED BY STORM-CHARACTERISTICS IN SOUTHERN CALIFORNIA MOUNTAINS

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Problems of water-supply, irrigation, flood-control, agriculture, and other projects in land-use management demand an accurate measure of precipitation. In southern California, where the mountains rise abruptly from populous valley plains, it is important that adequate measurements be made at the source of the water-supply. The management of mountainous, chaparral-covered watersheds has presented sufficient problems to warrant the undertaking of watershed-research by the Forest Service of the United States Department of Agriculture. In 1933 hydrologic studies directed toward this end were initiated on the San Dimas Experimental Forest [see 10 of "References" at end of paper], a branch of the California Forest and Range Experiment Station.

One of the first tasks on this project was to obtain reliable measurements of precipitation on the watersheds under study. More than 300 rain-gages were placed throughout the Forest. The Experimental Forest, shown on the relief map of Figure 1, comprises two sharply dissected watersheds, Big Dalton Canyon and San Dimas Canyon, in the south front of the San Gabriel Mountains. The former ranges in elevation from 1,500 to 3,400 feet in 3.5 miles, while the latter rises from 1,500 to 5,400 feet in a distance of some 5.5 miles. This indicates generally steep slopes, actually from 30 to 120 per cent. The average slope of the whole area is estimated to be 60 per cent. The aspect of the watersheds as a whole is southerly. Consequently, extensive north exposures are almost entirely lacking, but minor north exposures are included in the general makeup of the major east and west aspects.

The scheme for distribution of the rain-gages has been described [16, 19] and an analysis of the first three years' data showed that the method of sampling was statistically adequate [19]. Although these data indicated that a good distribution of samples had been obtained, there was no assurance that the vertically placed gages gave true measures of rain-catch by watersheds. In fact, the variations in individual gage-records indicated that further knowledge of the behavior of rainfall on rugged terrain would be necessary before it could be considered that the exposure as well as the distribution of gages in a watershed was competent to give an accurate measure of precipitation-catch.

From a review of the literature it appears that very little research had been done on the subject of behavior of rainfall in the mountains. Many studies had been conducted on variations of rain-catch by individual gages [7, 8, 11] and the effect of wind had been strongly emphasized [1, 2, 9], but these observations had almost without exception been made in country of minor relief. Studies conducted at Rotherham, England [11, 15], between 1865 and 1872 included observations of the effect of wind-velocity on the catch of gages at varying heights above the ground. Several special gages were designed for this purpose including a fixed five-funnel gage (Fig. 2C) and a rotating gage (Fig. 2A). HORTON, in listing the errors to which records of rainfall are subject [8], mentioned gage-location, wind-effect, and angle of inclination of the rain as factors requiring careful consideration. Again in a later paper [7] he gave a mathematical demonstration of the effect of the angle of inclination of rainfall on precipitation-catches in steeply inclined drainage-basins. In 1932 ROBERT PERS [13] demonstrated that in steep mountainous country precipitation-measurements by the conventional exposure of rain-gages gave erroneous results in which the errors were "far from negligible". He proposed that "plane rainfall-measurement" be changed to "space rainfall-measurement" and suggested a new type of rain-gage, a "stereopluviometer", whose funnel would be cut to simulate the slope and outline of the watershed in which it was installed. PERS also described an instrument called a "vectopluviometer" (Fig. 2B) with which the directional components of rainfall could be ascertained and by means of which the angle of inclina-

tion of rain could be determined [13, 14]. More recently, FOURCADE [5] has thoroughly covered the subject of behavior of rainfall in mountainous regions from a mathematical point of view. He proposed an instrument (Fig. 2E) for the determination of the (vertical and horizontal) components of rainfall, which is similar to the Rotherham five-funnelled gage and the PERS vectopluviometer. This publication also presented a somewhat similar gage (Fig. 2D) designed for the same purpose by WICHT.

A comparative study of rain-gage design, exposure, and placement was begun in 1936 at Tanbark Flat, the field-headquarters for the San Dimas Experimental Forest. The study has been described and the results published in so far as they dealt with variations in the catch of rain-gages [17]. The present paper deals with a second phase of the experiment: The behavior of storms with

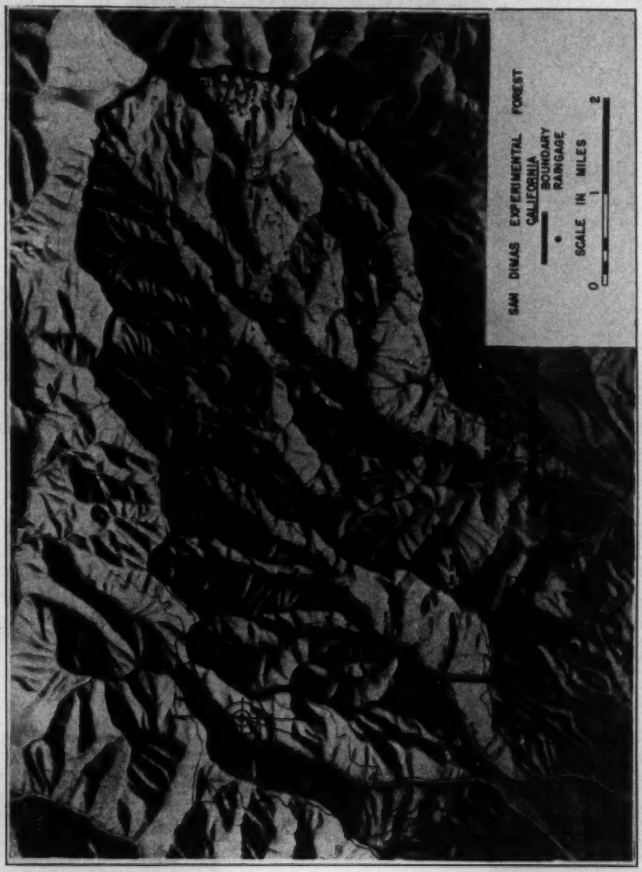

Fig. 1--Relief-map

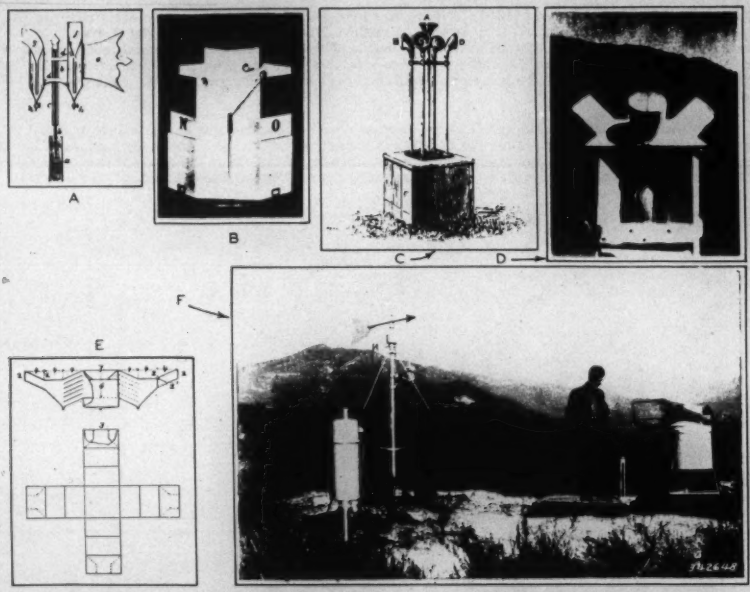

Fig. 2--(A) Rotating experimental rain-gage at Rotherham, England, 1865-1872; (B) vectopluviometer by Pers, France, 1932; (C) five-funnelled experimental gage at Rotherham, England, 1865-1872; (D) inclined rain-gage assembly by Wicht, South Africa, 1941; (E) composite rain-gage proposed by Fourcade, South Africa, 1941; (F) San Dimas vectopluviometer (right), tipping-bucket rain-gage (left), and wind-measuring instruments on Rain-Gage Hill, San Dimas Experimental Forest, California, 1937

regard to (a) rate and direction of rainfall, (b) wind-velocity and direction, and (c) the components of rainfall, including its angle of inclination from the vertical.

Experimental equipment and methods

General instrumentation--The instruments for this phase of the study included a wind-direction transmitter, an anemometer, a tipping-bucket rain-gage, and a directional rain-gage (Fig. 2F). These instruments were installed on a small hill, "Rain-Gage Hill," freely exposed to the prevailing wind [17]. Some 200 yards to the south and beyond the foot of the hill, another gage, designated as the "Tanbark Standard," was located in a small opening within a 15-year-old pine plantation. This gage was sheltered from direct winds and met all the requirements of the Weather Bureau for rain-gage location. Comparisons between this gage and other rain-measuring installations showed that it gave an excellent measure of the rainfall in that particular vicinity.

The performance of the first three instruments was recorded electrically and synchronously on a multi-pen recorder of the strip-chart type. The directional rain-gage was termed a vectopluviometer after the instrument described by PERS [13]. It was felt that such an aptly descriptive term deserved to be used more freely and not suffered to languish obscurely in loc. cit. This instrument was designed by Messrs. WILM and STOREY, then of the San Dimas Experimental Forest staff. It differs radically from PERS' "assemblage of four prismatic letter boxes" but supplies similar data.

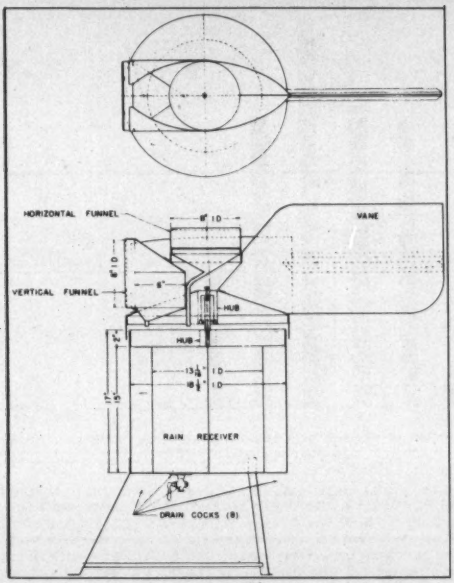

Fig. 3--Plan and vertical cross-section of the San Dimas vectopluviometer

The San Dimas vectopluviometer--This instrument consists essentially of a circular revolving head on which are mounted two eight-inch diameter rain-gage funnels (Figs. 2F and 3). One funnel is set in the center of the head with its rim in a horizontal plane; the other is set close to the periphery of the head with its rim in a vertical plane. This assembly is fitted with a tail or vane that keeps the vertical funnel headed into the wind and is mounted on a pivot-bearing centered over a receiver. This latter is a cylindrical tank divided into two concentric receptacles, each subdivided by septa into four compartments. A short section of tubing attached to each funnel directs the rain caught by the horizontal funnel into the interior compartments, and that caught by the vertical funnel into the outer compartments. Each compartment is provided with a separate drain-valve. The complete assembly is oriented so that north-south and east-west lines bisect the compartments. When the revolving head points to the south, the catch of the two funnels is deposited in the two south compartments of the receiver, that from the horizontally mounted funnel representing the vertical components of the rain and that from the vertical funnel giving the horizontal components. When the wind changes into a new quadrant the rain-catches shift to the appropriate compartments of the receiver. At the end of the storm the catches of the separate compartments are measured and converted to inches of rain.

The angle of inclination of the rainfall (i) from any quadrant can easily be calculated by the formula

$$\tan i = (V/H)$$

where V is the catch of the funnel with vertical rim and H is the catch of the funnel with horizontal rim. Or the average inclination of the whole storm can be determined by summing the catches and then applying the formula. Further, the predominant direction of the rain can be determined from

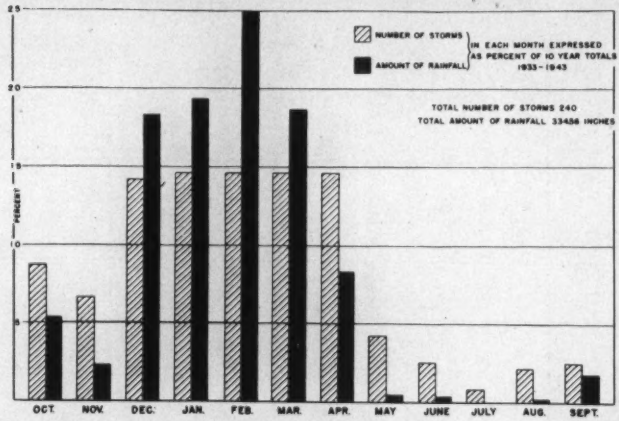

Fig. 4--Distribution of number of storms and amounts of rainfall by months for 10-year period 1933-43

the relative size of the horizontal funnel-catches. In this connection it is of interest to note that the British investigators, in so far as the writer has been able to ascertain, made no detailed analysis of their data concerning the directional components of rain by individual storms. Apparently, the main purpose of these early studies was to determine the optimum placement of rain-gages with reference to the height above the ground-surface and to their protection from wind. It was not until several years after the San Dimas vectopluviometer had been put into operation that the writer learned of the British work through SALTER'S publication [15].

Adequacy of sample--The data employed in the present study were drawn from rainfall-measurements made on the San Dimas Experimental Forest during the ten-year period, 1933-43. During that time there occurred 240 storms aggregating 334.56 inches whose monthly distribution is shown in Figure 4. Their distribution by size-classes (Fig. 5) brings out the fact that 112 storms or 44 per cent of the total number were of such small size--0.50 inch or less--that they produced only 18.45 inches of rainfall or only 5.5 per cent of the total ten-year catch. The small proportion of the total rain represented by these storms coupled with indications of considerable instrumental error in their measurement [19] decided the writer against employing these small storms in the present study. Furthermore, in many cases it was found that slight errors in measurement of these small quantities caused disproportionate variations in the vectopluviometer-computations. Consequently, all those storms totaling less than 0.50 inch were excluded from further consideration in the analysis.

In the seven-year period from initiation of the detailed study in 1936 to 1943, there occurred 173 storms which produced 250.97 inches of rain. Of the 97 storms over 0.50 inch in size recorded in this seven-year period, 37 had to be discarded because of faulty measurements, instrumental accidents, etc. This left 60 storms aggregating 163.40 inches of rain for which all data were complete and upon which detailed analysis was made. This group of storms was designated the "vecto-sample". The number and amount of the storms expressed as percentages of the totals in both the seven-year period and the vecto-sample, are shown as bar graphs in Figures 6 and 7, respectively. It is plain that the storm-distribution throughout the size-classes is sufficiently comparable to justify the assumption, without recourse to further statistics, that the 60 storms represent a reliable sample of the rainfall under consideration.

Analysis

The data obtained from the experimental installation and represented by the vecto-sample were analyzed to determine:

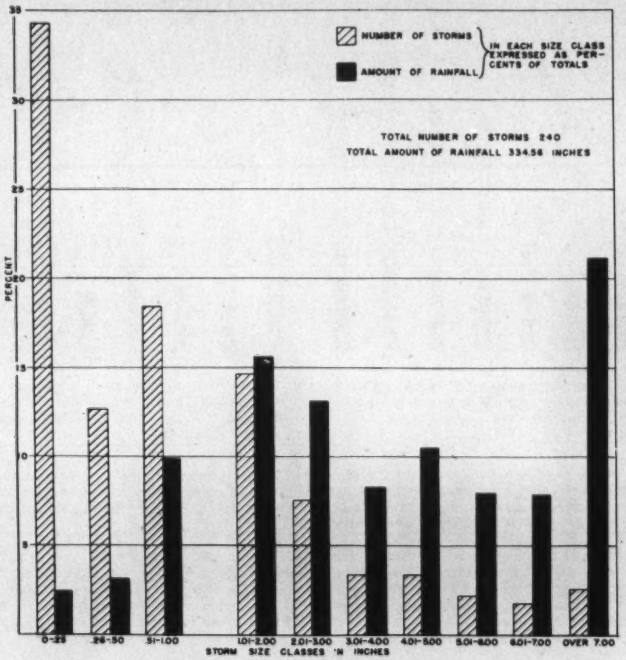

Fig. 5--Distribution of total number of storms and amounts of rainfall by storm-size classes for 10-year period 1933 - 43

(1) The patterns of rain-storms and their classification
(2) The predominant direction of storms
(3) Relationship between storm-patterns and (a) angle of inclination of rainfall, (b) wind-velocity, and (c) rainfall-rate
(4) Computation of the angle of inclination of rain by means of wind-velocity and rainfall-rate
(5) The effect of wind and inclination of rain on the catch of rain-gages in exposed sites
(6) How rainfall-measurement can be bettered through application of the principles herein developed

Construction of storm-patterns--The term "storm-pattern" is herein applied to the graphic presentation of the rainfall for any given storm as a geometrical figure developed upon either four or eight principal directions of the compass as polar coordinates, the length of the coordinate in each case representing the quantity of rain which came from the direction indicated. The plotting of synchronized records of rain and wind from a recording rain-gage and a wind-direction transmitter produced the patterns in Figure 8. The plotting of the data from the vectopluviometer produced the patterns in Figure 9, in which the patterns are limited to four points. In the vecto-patterns the vertical rain-components caught by the horizontal funnel usually formed the outer perimeter of the pattern (black area), while the horizontal components caught by the side or vertical funnel in most cases formed the inner perimeter (white).

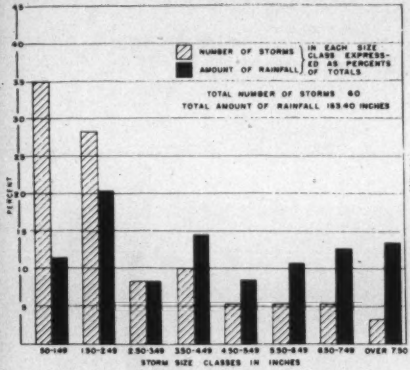

Fig. 6--Distribution of number of storms, 0.50 inch or more in size, and amounts of rainfall by storm-size classes for 7-year period 1936 - 43

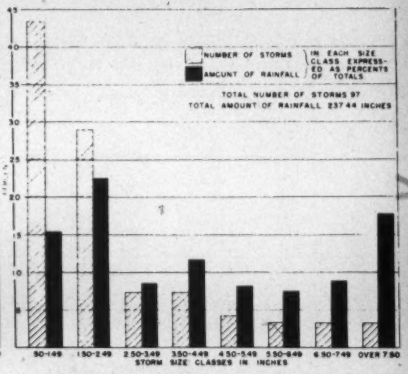

Fig. 7--Distribution of number of storms 0.50 inch in size and amounts of rainfall by storm-size classes, in the Vecto sample for the 7-year period 1936 - 43

Each storm considered in this study includes all of the precipitation which may be attributed to the disturbance under consideration including the instability showers which may occur some hours after the final frontal passage. Since the rainy season in southern California occurs chiefly during the winter months the storms under study are exclusively cyclonic in nature.

It was found that many of the storm-patterns were similar and that after a number of arrangements based on shape alone they fell into several definite groups governed by the predominant direction from which rain came. Three major groups became evident, two of which were susceptible of division into two and four sub-groups, respectively. The groups were decided upon, first by alternate arrangement and scrutiny of both the vectopluviometer and tabulated wind-direction patterns, and second by the following criteria:

Group (A)--Storms containing over 50 per cent north rain

Group (B)--Storms containing 30 per cent or more north rain and sub-divided into

(B-1)—Storms of the shifting type, in which there are frequent wind-changes and in which the storm gradually develops from several directions. These storms appear to fit the following description by BROWN [4]: "A frequent behavior of the east-southeast type is that the LOW center moves to about latitude 32° or 33° north and longitude 125° west where it stops or describes a small loop over a period of from one to three days, causing much precipitation in southern California meanwhile."

(B-2)—Two-phase storms where the rain usually comes first from the north and then switches into the south.

Group (C)—Southerly storms--containing usually much less than 25 per cent north rain and subdivided into

(C-1)—Rain predominantly from the south

(C-2)—Rain from southwest and southeast

(C-3)—Rain from the southeast

(C-4)—Rain from the southwest

Obviously, the vecto-sample contains some storms that are border-line cases. The percentage of north-rain criteria were established to assist in the definition of the storm-groupings. These criteria have been rigidly followed except in the case of storms Nos. 1 and 35 in Group (C-1). These two combine the form-characteristics of groups (B-1), (B-2), and (C-1), and since they contain a considerable proportion of north rain (34-40 per cent), they might well be assigned to one of

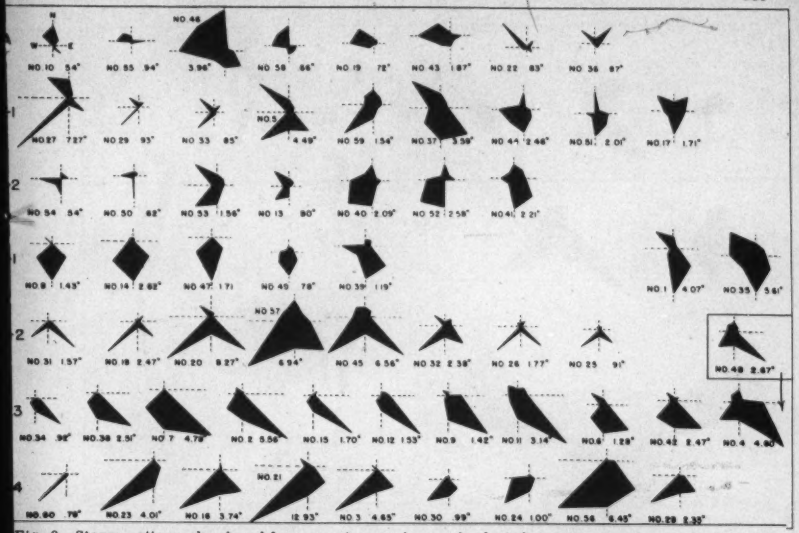

Fig. 8--Storm-patterns developed from synchronized records of wind-movement and rainfall, 1936-43, San Dimas Experimental Forest, California (not drawn to scale)

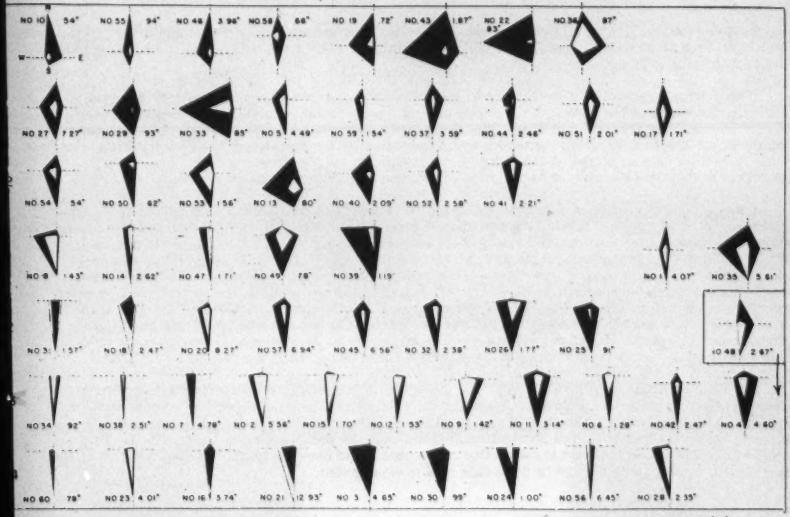

Fig. 9--Storm-patterns developed from vectopluviometer data, 1936-43 (not drawn to scale)

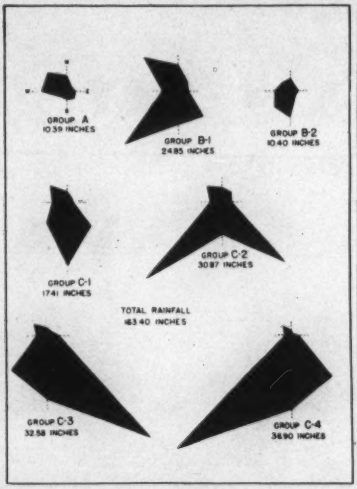

Fig. 10A--Composite patterns drawn to scale of the total rainfall in each storm-group shown in Figure 8 (wind-direction and rainfall-data)

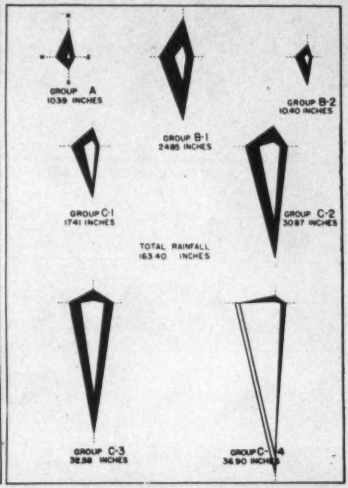

Fig. 10B--Composite patterns drawn to scale of the total rainfall in each storm-group shown in Figure 9 (vectopluviometer-data)

the former groups. However, a careful study of their vectopluviometer-patterns and other characteristics, such as rainfall-intensity and inclination which will be discussed later, showed that they really belong in Group (C-1).

The patterns within each group were arranged according to degrees of similarity in both the vectopluviometer and the tabulated direction-patterns and without regard to date of occurrence or size of storm. In Figures 8 and 9, showing the grouping by both types of patterns, the identical arrangement has been followed. Each storm is identified by the storm-number at the left and the total rain-catch of that storm at the right. In both Figures the patterns are not drawn to scale; however, in Figure 8 the size of patterns roughly corresponds to the size of storm.

Predominant direction of storms--In Figure 10 (A and B) a composite pattern of each storm-group has been drawn to scale in order to show the relative amounts of rain in each group. From these composite patterns it can be seen that the storms of Group (A) produced only six per cent of the total rainfall in the vecto-sample and the storms of Group (B-1) and Group (B-2) produced 15 and six per cent of the total, respectively. However, these first three groups, called predominantly northerly storms from the fact that they contain over half (55 per cent) of the north rain, produced only 28 per cent of the total. The (C)-groups of storms (southerly) accounted for 72 per cent of the total rainfall with the (C-4), or southwest, storms as the chief producers with 23 per cent. In short, although almost half of the storms came from the north, they produced considerably less than one-third of the total rain while the southerly storms produced more than two-thirds of it.

It should be made clear at this point that these storm-directions do not represent the directional track of cyclonic disturbances producing the rain, but merely the direction of local wind during the period of rain. An attempt was made to correlate the above storm-directions with a classification by BROWN [4] but no significant trend could be found except in Group (B-1). This is undoubtedly due to the fact that the direction of the local wind depends on the varying position of the barometric centers with regard to the locale of this experiment.

Table 1--Distribution of storms by rainfall-inclination classes

Class-interval, according to angles measured from vertical								
1	2	3	4	5	6	7	8	9
0° - 7°	7°-14°	14°-21°	21°-28°	28°-35°	35°-42°	42°-49°	49°-56°	56°-63°
	No.[a] °	No.[a] °	No.[a] °	No.[a] °	No.[a] °	No.[a] °	No.[a] °	No.[a] °
.....	10, 13	13, 18	4, 24	1, 29	2, 39	3, 47	21, 54	18, 57
.....	22, 8	19, 14	5, 26	9, 34	8, 36	7, 46	... ...	... ...
.....	25, 14	24, 19	6, 27	12, 30	15, 38	16, 49	... .	... ...
.....	29, 8	27, 20	11, 24	14, 32	23, 41	30, 45	... ...	... ...
.....	43, 11	33, 18	17, 25	20, 33	34, 35	31, 44	... ...	... ...
.....	50, 11	39, 19	26, 22	28, 34	38, 41	... ...	... ...	... .
.....	... ...	40, 15	32, 24	35, 30	47, 41	... ...	... ...	... ...
.....	... ...	42, 19	37, 22	36, 34	60, 41	... ...	... ...	... ...
.....	... ...	44, 14	41, 22	48, 32	... ...	... ...	... ...	... ...
.....	... ...	46, 15	45, 22	56, 34	... ...	... ...	... ...	... ...
.....	... ...	52, 19	49, 28	... ...	... ...	... ...	... ...	... ...
.....	... ...	54, 18	51, 24	... ...	... ...	... ...	... ...	... ...
.....	... ...	55, 15	53, 28	... ...	... ...	... ...	... ...	... ...
.....	... ...	58, 17	57, 22	... ...	... ...	... ...	... ...	... ...
.....	... ...	59, 17	... ...	... ...	... ...	... ...	... ...	... ...
No. cases	6	15	14	10	8	5	1	1
Pct	10.0	25.0	23.3	16.7	13.3	8.3	1.7	1.7

Totals: No., 60; percentage 100

[a] Serial number of storm.

Table 2--Average angle-class[a], weighted wind-velocity[b], and rainfall-rate[c] for 60-storm sample

Group A													
Storm-number	10	55	46	58	19	43	22	36					
Angle-class	2	3	3	3	3	2	2	5					
Weighted wind-velocity	2.1	1.1	2.8	0.8	3.1	2.3	2.2	5.1					
Weighted rainfall-rate	0.10	0.13	0.26	0.07	0.12	0.23	0.28	0.29					
Group B-1													
Storm-number	27	29	33	5	59	37	44	51	17				
Angle-class	3	2	3	4	3	4	3	4	4				
Weighted wind-velocity	2.0	1.9	3.0	3.7	1.9	4.5	2.5	3.7	4.6				
Weighted rainfall-rate	0.33	0.08	0.25	0.22	0.33	0.40	0.17	0.24	0.25				
Group B-2													
Storm-number	54	50	53	13	40	52	41						
Angle-class	3	2	4	3	3	3	4						
Weighted wind-velocity	1.3	1.8	4.2	1.8	2.5	2.6	3.7						
Weighted rainfall-rate	0.07	0.17	0.29	0.13	0.21	0.23	0.42						
Group C-1													
Storm-number	8	14	47	49	39	1	35						
Angle-class	6	5	6	4	3	5	5						
Weighted wind-velocity	5.3	4.8	5.8	1.8	2.8	2.8	5.4						
Weighted rainfall-rate	0.54	1.48	0.38	0.12	0.69	0.25	0.53						
Group C-2													
Storm-number	31	18	20	57	45	32	26	25					
Angle-class	7	9	5	4	4	4	4	2					
Weighted wind-velocity	7.0	11.8	5.0	3.0	3.4	2.8	2.1	2.6					
Weighted rainfall-rate	0.28	0.55	0.41	0.46	0.79	0.20	0.32	0.27					
Group C-3													
Storm-number	34	38	7	2	15	12	9	11	6	42	4	48	
Angle-class	6	6	7	6	6	5	5	4	4	3	4	5	
Weighted wind-velocity	6.4	5.1	7.5	5.8	6.0	4.7	4.2	2.7	2.7	2.6	2.1	4.8	
Weighted rainfall-rate	0.33	0.41	0.39	0.33	0.24	0.34	0.15	0.21	0.10	0.29	0.28	0.31	
Group C-4													
Storm-number	60	23	16	21	3	30	24	56	28				
Angle-class	6	6	7	8	7	7	3	5	6				
Weighted wind-velocity	3.1	6.5	6.8	10.1	8.2	6.6	3.0	5.0	5.0				
Weighted rainfall-rate	0.15	0.53	0.35	0.71	0.38	0.23	0.39	0.45	0.45				

[a] Refer to Table 1 for class-intervals. [b] Miles per hour. [c] Inches per hour.

Table 3--Storm-group summary

Group	Number storms	Total amount rain	Angle of inclination from vertical	Wind-velocity	Rainfall-intensity
		in	°	mph	in/hr
A	8	10.39	15	2.6	0.22
B-1	9	24.85	20	3.1	0.28
B-2	7	10.40	20	2.9	0.25
Subtotal	24	45.64	..	...	...
Average, combined northerly groups	..	....	19	2.9	0.25
C-1	7	17.41	31	4.4	0.45
C-2	8	30.87	29	4.4	0.48
C-3	12	32.58	33	4.6	0.33
C-4	9	36.90	45	7.5	0.50
Subtotal	36	117.76			
Average, combined southerly groups	..	....	35	5.4	0.44
Grand total	60	163.40	..	...	...

Angle of inclination--The vectopluviometer facilitated determination of the angle of inclination of the rainfall from the vertical. A knowledge of this function of rainfall is useful in the measurement of precipitation on steep mountainous watersheds. That sharply inclined rain falling on sharply inclined slopes cannot be measured accurately in vertically placed gages has been mathematically demonstrated by HORTON, PERS, and FOURCADE [7, 13, 5]. While all of these writers dealt with the mathematical theory, PERS, in particular, emphasized the need for field-research to test its validity and to accumulate essential data.

The angles of inclination for the 60 storms in the vecto-sample were computed as indicated under "Description of vectopluviometer" The segregation of the vertical and horizontal components of the rain by quadrants made it possible to determine the angle for each of the cardinal directions of the storm. However, we shall deal only with the average angle of the storm since it was found that this angle corresponded closely with the angle of the principal directional catch of rain.

The angles of the storms in the vecto-sample are set forth in Table 1 as nine classes in accretions of 7°. These angles range from 7° 44′ to 56° 51′. Only ten per cent of the storms occurred at an angle less than 14° but 48.3 per cent fell in the two classes of 14° to 21° and 21° to 28° In the remainder of the storms--amounting to 41.7 per cent of the total number--the rain was inclined 28° to 56° from the vertical, a not inconsiderable amount. When the angles of inclination are correlated with the storm-patterns, a most interesting relationship appears. In Table 2 the angle-of-inclination classes are arranged in the same order as the patterns in Figures 8 and 9. We find that all the north storms [Group (A)] fall into classes (2) and (3), with one exception, and that the average angle is 15°. Likewise the two sub-groups of (B)-storms fall in the lower-angle classes, but the increasing number of Class (4) angles brings the average of the two rows to only 20° As the storms become predominantly southerly, the angle of inclination makes a marked increase and for Group (C-1) goes to 31°. Group (C-2) shows a slight drop to 29° but in Group (C-3) the angle rises to 33°, and in Group (C-4) it has increased to 45°. Although more than half of the storms exhibit comparatively small angles of inclination--7° to 28°--we find that these small angles are characteristic of the northerly storms while the larger angles are characteristic of the southerly storms, which bring most of the rain and which are of hydrological importance. These relationships are clearly shown in Table 3 where the storms have been summarized both as groups and as combinations of the (A), (B-1), (B-2) [northerly] and (C-1), (C-2), (C-3), (C-4) [southerly] groups.

The above relationships are indicated also by the vectopluviometer-patterns in Figure 9. In the formula, $\tan i = (V/H)$, the angle increases as V approaches H in magnitude. Accordingly, as the rainfall-angle increases the white portion of the pattern approaches or surpasses in size the black portion. This trend progresses from Group (A) to Group (C-4) storms. The relationship is still more strongly emphasized in Figure 10-B where composite patterns for each storm-group of Figure 9 have been constructed and drawn to scale.

Relationship between the angle of inclination and wind-velocity--In order to show graphically the relationship of wind-velocity to the angle of inclination of rain, the data employed in Figure 8 were plotted on rectangular coordinate paper as mass-curves of rainfall over time and of total wind-miles for each change in direction. The rain-curves were broken into periods of uniform rate from which rainfall-intensity was computed in inches per hour. The wind-velocities for these same periods were computed in miles per hour. The rainfall-rates and wind-velocities were then indicated at the bottom of the graph as a series of vertical bars in which the duration of the rate was indicated by the width and its magnitude by the height. Two sample graphs are presented in Figure 11.

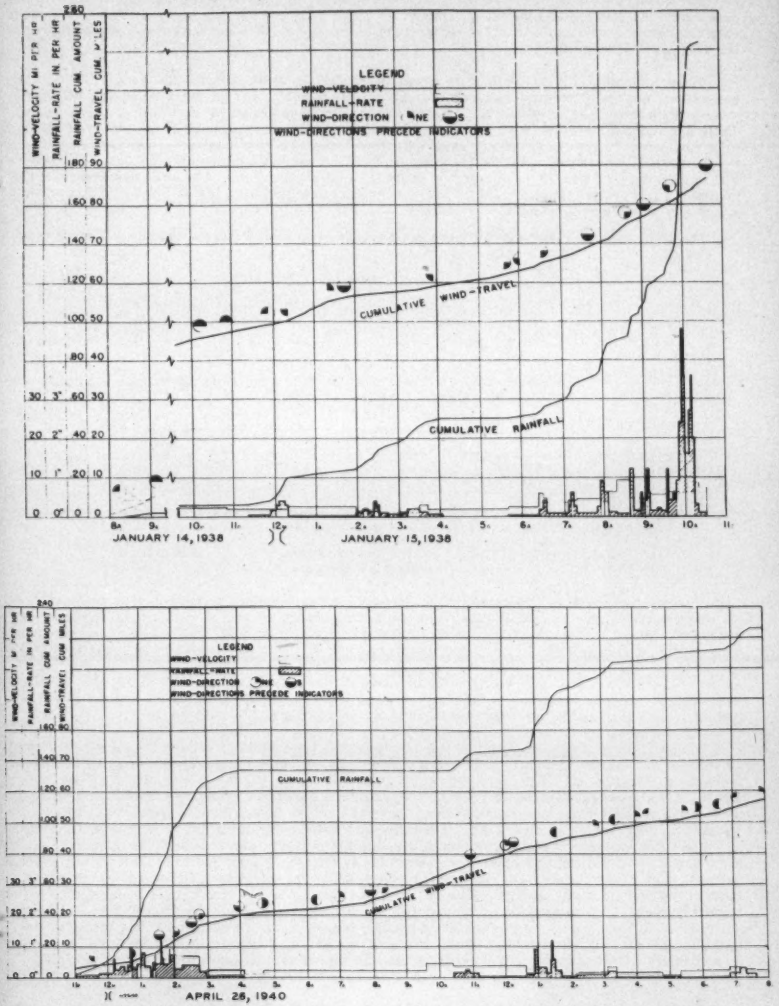

Fig. 11--Sample graphs of cumulative wind-travel and rainfall used for computation of weighted wind-velocity and weighted rainfall-intensity (Storm No. 14, upper; No. 41, lower)

The wind-velocity for each rainfall-rate period was weighted by the actual amount of rain occurring during that period, and the summation of these weighted periods when divided by the storm-rain total gave a value called the "weighted wind-velocity" (V_W), which was then used as the wind-velocity index for the storm.

These weighted wind-velocities are shown in Table 2 in which the storms are arranged in the same order as the storm-patterns in Figure 8. It will be noted that the wind-velocities follow the same trends as the angles of inclination throughout the classes from (A) to (C-4) and again in Table 3 a marked increase in wind-velocity is shown as the storms change from northerly to southerly. In Figure 12 the observed angles of inclination of the rain have been plotted against the weighted wind-velocities for the vecto-sample. Here the relationship takes the form of a curve that flattens as the value of V_W increases beyond five miles per hour. The wide dispersion of the points at the lower velocities is due to the inaccuracy of the anemometer at low velocities. The derivation of the equation is discussed later.

The wind and rain mass-curves were again used to determine a value called the "weighted

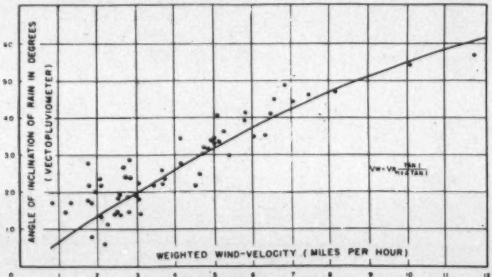

Fig. 12--Relationship between weighted wind-velocity and angle of inclination of rain

rain-intensity" (I_r). This was computed in the same manner as the "weighted wind-velocity" (V_W) by weighting the uniform rainfall-rates with the actual amount of rain in the uniform rate-periods and dividing their sum by the storm-total. These rates are also shown in Table 2 and again it may be seen that, although there is not a very good correlation of rainfall-intensity with angle of inclination within the directional class-grouping, the rate increases, as a rule, with the increasing amount of south rain and reaches a maximum (0.44 inch per hour) in Group (C-4). Table 3 indicates that the average intensity of the combined southerly groups is 87 per cent greater than the intensity (0.25 inch per hour) of the combined northerly groups.

Computation of the angle of inclination of rain--The inclination of rain is the resultant of the velocity of the wind and the rate of fall of the raindrops. It can be computed from values obtained from the graph (Fig. 12) by the formula $\tan i = (V_W/V_T)$, where V_W is the weighted wind-velocity and V_T is the terminal velocity of the rain corrected for vertical updraft. V_T is obtained by referring the rainfall-rate, I_r, computed from the graph, to the table given on page 280 of HUMPHREY'S "Physics of the air" where intensities are paired with terminal velocities and the assumption is made that raindrop-size is uniform for the intensity used. A simpler approach would be to use several different levels of terminal velocity (high, medium, and low) instead of a separate one with each change in rainfall-rate. The results, however, would be little changed because in most of the storms under consideration the terminal velocity of the rain varies from nine to eleven miles per hour (22 per cent), as compared with variations in wind-velocity from two to ten miles per hour or 500 per cent. Approximately the same results would be obtained if one terminal velocity for all kinds of storms were used. In short, the factor of terminal velocity could be regarded as a constant. Thus it is seen that the chief determinant of variations in the angle of rainfall-inclination is wind, the velocity of which can be measured directly.

The terminal velocity must be corrected for the vertical updraft of wind since this component is the natural resultant of horizontal wind impinging on a steep mountain side [14]. This correction was effected by reducing the given terminal velocity of 40 per cent of the observed horizontal wind-

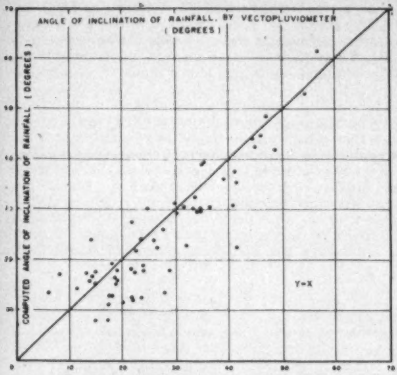

Fig. 13--Computed angle of inclination of rain plotted against angle of inclination derived from vectopluviometer-data)

velocity. This factor was derived from the actual slope of Rain Gage Hill. The formula now becomes $\tan i = [V_w/(V_r - 0.4\ V_w)]$. This is the procedure developed by HUDLESTON [9] in his studies on the effect of sloping terrain on the catch of a rain-gage. The equation $V_w = [V_r \tan i/(1 + 0.4 \tan i)]$ for the fitted curve in Figure 12 was derived by solving for V_w in the above equation. The computed values of the angles of inclination for the storms of the vecto-sample, plotted against the observed values from the vectopluviometer, are shown in Figure 13. The grouping of points about the 45° line indicates the close relationship between wind-velocity, rainfall-rate, and the angle of inclination of rain.

The effect of wind and inclination of rain on the catch of rain-gages in exposed sites--Mention has been made under "Experimental equipment" of the rain-gage known as the "Tanbark standard". A comparison of its catch with the catch of a circular concrete surface ten feet in diameter and situated at ground-level indicates that the catch of the gage is an accurate sample of the rain actually reaching the ground. In Figure 14 the percentage-differences in catch between this gage and a standard gage on a nearby hill were plotted against the angle of inclination of the rain. A line

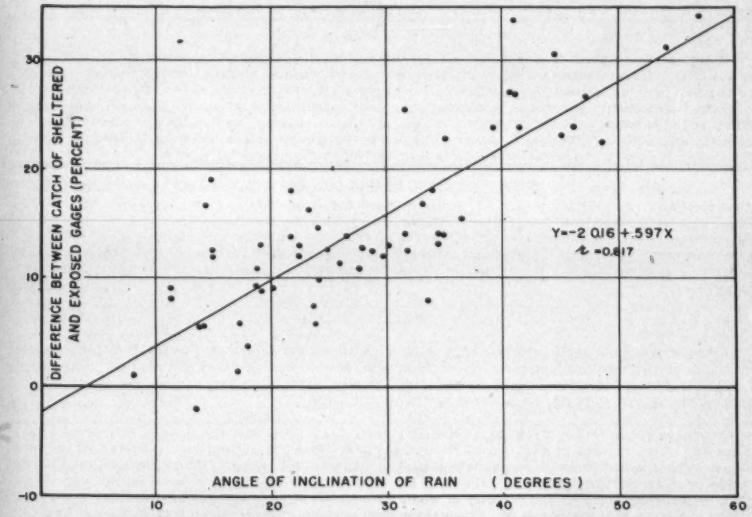
DIFFERENCE BETWEEN CATCH OF SHELTERED AND EXPOSED GAGES (PERCENT)
Y=-2.016+.597X
r =0.817
ANGLE OF INCLINATION OF RAIN (DEGREES)

Fig. 14--Relationship between the percentage-difference in the catches of two gages (sheltered) and exposed), and the angle of inclination of rain

was fitted to the points by the method of least squares, and its correlation-coefficient of 0.817 indicates a good degree of correlation in view of the dissimilarity of the two variables. The hilltop gage was exposed to the full sweep of the prevailing winds and, as the wind-velocity and sequentially the angle of inclination of the rain increased, the percentage-difference in catch between the two gages increased. For purposes of practical rainfall-measurement in the mountains, sites like that of the hilltop gage give misleading results.

How rainfall-measurement can be bettered through application of the principles herein developed--It has been shown that the greater proportion of the rainfall on the San Dimas Experimental Forest comes from a southerly direction and that in these southerly storms the rain falls at a considerable angle from the vertical. Under these conditions, and since the watersheds under study have predominantly southern exposures, it follows, from the demonstrations of PERS [13] and FOURCADE [5], that the rain-catches of the conventional vertical rain-gages should be low. In the case of northerly storms it has been found that the rain generally is inclined at a very small angle from the vertical and that this inclination influences very slightly the gage-catches. However, if the northerly storm should be highly inclined, as in storm No. 36 (Fig. 9), the gage-samples will be in excess of the true amount.

In view of these findings it is apparent that rain-gages in the San Dimas Experimental Forest require adaptation to the rainfall-characteristics. In particular, the ring or cutting edge of the rain-gage must be placed parallel to the watershed-slope on which the gage stands and for which it is a sampling medium. One method of doing this is by slanting the cutting edge itself of the funnel to bring it parallel to the slope of the watershed. This is, in effect, a simplification of the stereopluviometer proposed by PERS and used successfully by HAYES [6]. Another and simpler method is to tilt the standard gage sufficiently to bring its vertical axis normal to the average slope of that portion of the watershed to be sampled, as advocated by PAGLIUCA [12] and BROOKS [3]. Gages tilted in this manner, as well as sloping-funnel gages like those of HAYES [6], were shown by STOREY and the writer [17] to give more representative samples of precipitation than standard vertical gages.

Observations by STOREY and WILM [18] of the performance of paired tilted and vertical gages installed throughout a small watershed are reported elsewhere in this number of the Transactions [pp. 518-523].

It appears conclusive that velocity and direction of wind, ground-slope, and inclination of rainfall all have a marked influence on rainfall-measurement in standard gages conventionally placed, and that the reliable measurement of rainfall in mountain areas requires either the application of correction-factors to the records of standard gages or the tilting of standard gages to bring their cutting edges parallel with the slopes which the gages represent. A method for the correction of past rainfall-records, in the light of the principles herein developed, is being formulated for application to ten years of rainfall-records in the San Dimas Experimental Forest.

This discussion has been limited to means of improving the measurement of total rain-catch by a watershed. The factors which affect the catch of the ordinary standard gage affect the recording gage as well. Since recording-gage records are of the utmost importance in hydrologic analyses, it would be well to insure that their records represent the proper rate of delivery of rainfall to the watershed. Preliminary studies now under way indicate that, because of high angles of inclination, maximum rainfall-intensities recorded by conventional gages vary appreciably from the true intensity.

Summary

A study was made of the precipitation on the San Dimas Experimental Forest in the San Gabriel mountains of southern California with particular reference to the direction and angle of inclination of rainfall. Out of 173 storms which produced 251 inches of rain in a seven-year period, a representative sample of 60 storms was subjected to detailed study.

From the records of a directional rotating rain-gage, it was found possible to determine what proportion of the rainfall in each storm entered the gage from each of the four cardinal sectors of the compass, and to calculate the average angles of inclination of the rain from the vertical. From a study of simultaneous records of rainfall of the same storms as recorded in an intensity-gage, and of records of direction and velocity of wind, the rainfall of each storm was allocated to eight directional sectors of the compass. From these data graphic representations of storm-patterns were developed which permitted classification of the storms on the basis of direction from which the rain fell. These data also made possible the computation of the angle of inclination of the rain.

This study has supplied information concerning the behavior of storms and the rainfall occasioned by them, with particular reference to southern California mountain conditions.

It was found that northerly storms usually produce small amounts of precipitation occurring generally at low intensity and at only slight inclinations from the vertical. Southerly storms, on the other hand, are the great rain-producers; and their precipitation is usually of much greater intensity than the northerly storms. The southerly storms are accompanied by higher winds than the northerly storms, and their precipitation usually is inclined a considerable amount from the vertical. These findings further explain the differences in rain-catchment by paired vertical and tilted gages reported from another study in the same vicinity [19].

Southern California storms follow definite patterns which can readily be classified. These storm-groups have definite characteristics whose interpretation is necessary to determine the proper distribution and exposure of rain-gages on a watershed to insure the accurate measurement of precipitation. These findings also can be used for the correction and interpretation of past rainfall-records in this region, and the principles developed should have universal application.

Acknowledgment is made to the Glendora Civilian Public Service Camp No. 76 for assistance in the presentation of this paper and especially to KENNETH D. ROOSE of the camp whose indefatigable efforts in the assembly and compilation of the data as well as his leading part in the analysis have been invaluable. Credit is also due to other members of the camp who were associated with the work, namely: P. B. JOHNSON and R. C. JAMES--mathematical assistance; L. W. HARRISON, D. D. HALL, E. A. VAIL, and J. C. THOMPSON--wind-and-rain tabulation; K. C. SOUTHARD--typing; H. G. BUSH and D. C. MARIS--computations; and S. C. EDINGER, H. C. CRAWFORD, F. W. BUCKLER, and V. G. PANUCCI--development of graphical presentation of data and drafting.

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A COMPARISON OF VERTICAL AND TILTED RAIN-GAGES IN ESTIMATED PRECIPITATION ON MOUNTAIN WATERSHEDS

H. C. Storey and H. G. Wilm

When, in hydrologic research, we need to measure the cubic volume of water precipitated on a mountain drainage-basin, conventional methods of precipitation-measurement may be open to some question. In ordinary practice, for example, a number of standard rain-gages may be installed in a watershed with their funnels in the usual horizontal plane. The depths of water caught in these gages may then be associated, by any one of several methods, with the projected (map) area of the watershed in order to calculate the total cubic volume of precipitation which fell on the watershed.

While this method may be quite reliable on tracts of comparatively level or gently rolling land, it may lead to serious errors on watersheds of rough topography, with steep slopes and facets of various areas and exposures. As discussed in detail by FOURCADE [see 3 of "References" at end of paper], these errors are due largely to the incidence of different volumes of precipitation upon sloping surfaces of different areas and exposures, when wind drives the falling drops at angles which deviate substantially from the vertical. With standard vertical gages, approximately equal amounts of precipitation might be measured on each facet of the basin; whereas in fact one facet might receive a much greater depth of catch than another. And if the various facets are unequal in area, it is easily seen that substantial errors in calculated cubic volume of catch may result.

If we may accept the validity of this principle, the simplest solution of our problem would seem to lie in the use of a number of gages, each exposed with its funnel edge parallel to the ground-surface of the facet it represents rather than horizontal. By this means each gage should catch a volume of precipitation more nearly in proportion to that which strikes the surrounding watershed-surface. The idea is not new; it was proposed as early as 1889 by FOURCADE [2] and the principles have been discussed more recently by FOURCADE [3], HORTON [4, 5], and others. The only real complication is in the calculation of cubic volume of precipitation for the basin. Even this procedure may be considerably simplified, however, if the rain-gages are randomized in location or distributed in a representative manner over the watershed so that each exposure is sampled in approximate proportion to the area it occupies. Then cubic volume may be obtained simply by (a) expressing the catch in each gage as depth in inches on the horizontally projected (elliptical) area of the gage, (b) averaging all of these adjusted depths, and (c) applying the average depth to the horizontal area of the watershed. The precision of this method may be increased by subdividing the watershed into areal strata dependent upon exposure, elevation, etc., and assigning one or more gages to each stratum [8].

By this method the use of tilted standard rain-gages for sampling precipitation becomes relatively simple and requires no new and complicated instruments or methods of analysis. The agreement between catch in tilted gages and catch at the ground-surface has been demonstrated by STOREY and HAMILTON [9]. Since, however, the resulting improvement in calculations of cubic volume will be largely affected by the actual inclination of rainfall as it strikes the watershed, and by the relative areas of the various watershed-facets, it appeared worth while to study the comparative catch of vertical and tilted gages in typical watersheds. The purpose of this investigation was to make such a comparison, in order to provide a mass of empirical data from which to determine the relative errors of vertical gages in estimating watershed precipitation.

Description of study--The study herein described was conducted on the San Dimas Experimental Forest [6]. This 17,000-acre area, located in the Sierra Madre Mountains about 30 miles east of Los Angeles, has been set aside by the United States Forest Service for the study of watershed-management problems. In this investigation the first important measurement is the volume of precipitation falling into various watersheds. To obtain this measurement a system of over 300 standard vertical rain-gages has been installed throughout the forest [10, 11].

A 100-acre watershed in Bell Canyon was selected for the rain-gage study. This area has been designated as Bell No. 2 Watershed (Fig. 1). The topography of this watershed is characterized by sharp ridges and steep slopes with exposures ranging from south to southwest and southeast. During storms the wind is usually from the southeast but occasionally from the northwest. Precipitation occurs almost entirely in the form of rain.

Twenty-two rain-gages were installed on four contour-trails located at elevations of 2,500, 2,800, 3,100, and 3,400 feet. A tilted gage was placed perpendicular to the ground-surface beside each vertical gage. All gages were read immediately after each storm for a period of four years, during which time 65 storms were recorded. These storms ranged in size from 0.06 inch to about 17 inches (as measured in the vertical gages).

In analysis, all readings for the tilted gages were corrected to give the amount of rain falling upon the horizontally projected area of the rain-gage funnel.

Results--As shown in Tables 1 and 2, the tilted gages recorded higher rainfall than the vertical gages in 54 out of 65 storms. Based on STUDENT'S "t" tests for paired observations [7], none of the negative differences were significantly greater than chance variation. Of the 54 positive differences, on the other hand, 42 were significant beyond the 0.05-level, and 33 of these beyond the 0.01-level. These tests, based on the variations between paired gages at 22 places in the watershed, indicate that tilting the gages resulted in a catchment which was generally significantly higher than that of the vertical gages.

In addition to these tests of differences between paired gages in individual storms, the general mean difference between vertical and tilted gages was also subjected to a statistical test. For this purpose the mean difference (over all storms, + 0.2554 inch) was compared with an estimate of error calculated from the fluctuations among mean differences from storm to storm ("mean

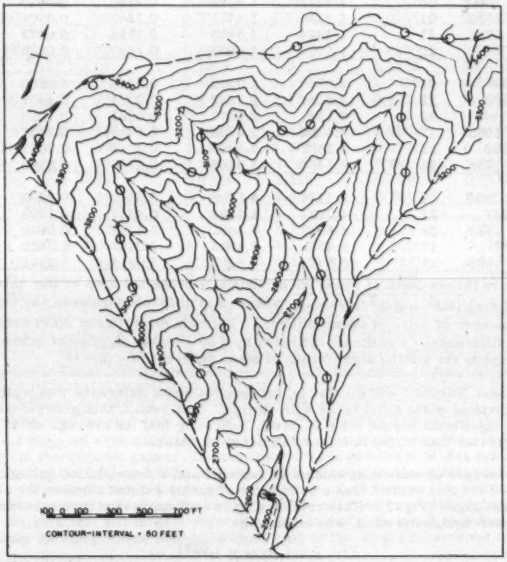

Fig. 1--Topographic map of Bell Canyon Watershed 2 (watershed-boundaries shown by dashed lines, contours by solid lines, and streams by dash-dot lines; circles indicate locations of rain-gages)

Table 1--Analysis of difference between tilted and vertical rain-gages, Bell Watershed No. 2, 1935-37

Date storm	Number gages read	Mean precipitation		Mean difference	Standard error of mean difference[b]	t[c]
		Tilted gage corrected[a]	Vertical gage			
		in	in	in	in	
Jan. 29, 1936	15	0.0593	0.0553	0.0040	0.0021	1.90
Jan. 7, 1937	16	0.1562	0.1388	0.0174	0.0109	1.60
Nov. 22-23, 1936	22	0.1295	0.1395	-0.0100	0.0050	2.00
Sep. 30-Oct. 1, 1935	10	0.1640	0.1470	0.0170	0.0067	2.54*
Mar. 27, 1937	22	0.1718	0.1664	0.0054	0.0094	0.57
Mar. 21-22, 1936	22	0.2355	0.2009	0.0346	0.0099	3.49**
Dec. 3-4, 1935	21	0.2838	0.2833	0.0005	0.0090	0.06
Dec. 3-4, 1936	22	0.3332	0.3068	0.0264	0.0102	2.59*
Mar. 17, 1937	22	0.3909	0.3141	0.0768	0.0167	4.60**
Apr. 2, 1937	22	0.3132	0.3268	-0.0136	0.0102	1.33
Nov. 17-18, 1935	20	0.3540	0.3475	0.0065	0.0093	0.70
Mar. 24, 1937	22	0.5232	0.5432	-0.0200	0.0200	1.00
Mar. 24, 1936	21	0.6714	0.6210	0.0504	0.0191	2.64*
Jan. 11-13, 1937	22	0.7827	0.7264	0.0563	0.0208	2.71*
Feb. 18, 1936	21	0.7700	0.8081	-0.0381	0.0275	1.39
Feb. 22-23, 1936	20	1.5345	1.2500	0.2845	0.0678	4.20**
Feb. 24-25, 1937	22	1.4627	1.3295	0.1332	0.0276	4.83**
Mar. 23, 1937	17	1.5553	1.4112	0.1441	0.0206	7.00**
Mar. 14-16, 1937	20	1.6915	1.4595	0.2320	0.0620	3.69**
Oct. 16-18, 1936	21	1.3129	1.4771	-0.1642	0.0901	1.82
Oct. 24-31, 1936	21	1.7424	1.5910	0.1514	0.0473	3.20**
Jan. 5-6, 1937	22	1.7777	1.6086	0.1687	0.0655	2.58*
Mar. 30, 1936	22	2.0245	1.7259	0.2986	0.0588	5.08**
Apr. 3-4, 1936	22	2.4441	2.2168	0.2273	0.0496	4.58**
Jan. 30-31, 1937	22	3.1341	2.6677	0.4664	0.1023	4.56**
Dec. 30-31, 1936	17	4.4206	3.3788	1.0418	0.2565	4.06**
Feb. 1-2, 1936	21	4.2305	3.4090	0.8215	0.2033	4.04**
Dec. 14-16, 1936	22	4.1464	3.9168	0.2296	0.0908	2.53*
Mar. 11-13, 1937	19	5.1184	4.2316	0.8868	0.2230	3.98**
Feb. 5-6, 1937	22	4.7927	4.3386	0.4541	0.1095	4.15**
Feb. 11-15, 1937	22	4.6627	4.3905	0.2722	0.0930	2.93**
Dec. 25, 1936	17	5.4935	4.4012	1.0923	0.2910	3.75**
Feb. 10-16, 1936	21	10.5771	9.5957	0.9814	0.2141	4.58**

[a] Corrected to give inches depth of water on horizontally projected area of the tilted funnel.

[b] Standard error = $\pm\sqrt{[\Sigma d^2 - (\Sigma d)^2/n]/n(n-1)}$ where d is difference between any pair of observations and n is number of pairs of observations. Formula used: (Mean difference/standard error of mean difference) = significant indicated by * or = highly significant indicated by **. [Degrees of freedom for testing significance of mean differences = (n - 1)].

difference" column, Tables 1 and 2); that is, the general mean difference was tested by the interaction of the individual mean differences with storms. As a result, this general mean difference was found to be significant beyond the 0.01-level, indicating that the average effect of tilting gages was decidedly greater than might have been expected by chance.

When the averages of individual storms in Tables 1 and 2 were plotted on logarithmic coordinate paper, it became evident that a definite relationship existed between the catches of the tilted and vertical gages (Fig. 2). This relationship is best expressed by an exponential equation which, by the least-squares method, was found to be

$$E = 1.0979 \times^{1.0251}$$

Table 2--Analysis of difference between tilted and vertical rain-gages, Bell Watershed No. 2, 1937-39

Date storm	Number gages read	Mean precipitation		Mean difference	Standard error of mean difference[b]	t[c]
		Tilted gage corrected[a]	Vertical gage			
		in	in	in	in	
Jan. 31-Feb.1, 1939	22	0.1236	0.1195	0.0041	0.0054	0.76
May 15-18, 1938	21	0.1352	0.1386	-0.0034	0.0062	0.55
Apr. 13, 1939	22	0.1909	0.1555	0.0354	0.0088	4.02**
June 9-12, 1938	20	0.1975	0.1790	0.0185	0.0081	2.28*
May 13-16, 1939	20	0.2180	0.2145	0.0035	0.0061	0.57
Apr. 12-13, 1938	21	0.2667	0.2243	0.0424	0.0108	3.93**
Jan.28-29, 1938	22	0.2386	0.2286	0.0100	0.0063	1.59
Jan. 19, 1938	22	0.2673	0.2582	0.0091	0.0048	1.90
Jan. 18, 1938	22	0.3086	0.2814	0.0272	0.0067	4.06**
Mar. 19-20, 1939	22	0.3568	0.3650	-0.0082	0.0122	0.67
Oct. 15, 1938	22	0.5605	0.4955	0.0650	0.0162	4.01**
Mar. 7-8, 1938	21	0.6310	0.6500	-0.0190	0.0187	1.02
Apr. 23-25, 1938	21	0.7976	0.7567	0.0409	0.0182	2.25*
Feb. 18-19, 1938	21	0.7581	0.7829	-0.0248	0.0339	0.73
Apr. 1-2, 1939	22	0.7900	0.7941	-0.0041	0.0293	0.14
Jan. 27-28, 30-31, 1939	22	0.7818	0.8009	-0.0191	0.0301	0.63
Apr. 28-May 2, 1938	21	0.9429	0.9062	0.0367	0.0265	1.38
Jan. 21, 1939	22	0.9568	0.9300	0.0268	0.0217	1.24
Dec. 26, 1937	22	0.9205	0.9441	-0.0236	0.0230	1.03
Dec. 22-23, 1937	22	1.2868	1.0905	0.1963	0.0416	4.72**
Mar. 9-10, 1939	20	1.4860	1.2045	0.2815	0.0736	3.82**
Dec. 14-16, 1938	22	1.8232	1.6282	0.1950	0.0641	3.04**
Feb. 3-8, 1939	15	2.0427	1.9453	0.0974	0.0807	1.21
Jan. 5, 1939	22	2.3891	1.9855	0.4036	0.0940	4.29**
Jan. 14-15, 1938	21	2.3852	2.0238	0.3614	0.0766	4.72**
Mar. 25-28, 1939	22	2.3795	2.2577	0.1218	0.0535	2.28*
Jan. 3-4, 1938	22	3.7718	3.0659	0.7059	0.1471	4.80**
Dec. 9-12, 1937	22	3.4814	3.1941	0.2873	0.0617	4.66**
Feb. 8-12, 1938	22	3.9305	3.3105	0.6200	0.1297	4.78**
Mar. 12-13, 1938	21	4.2119	3.4848	0.7271	0.1645	4.42**
Dec. 17-21, 1938	22	7.1859	6.7764	0.4095	0.1308	3.13**
Feb. 27- Mar. 3, 1938	21	20.6905	16.9795	3.7110	0.6303	5.89**

[a] Corrected to give inches of depth of water on horizontally projected area of the tilted funnel.

[b] Standard error = $\pm\sqrt{[S d^2 - (S d)^2/n]/n(n-1)}$ where d is difference between any pair of observations and n is number of pairs of observations.

[c] Formula used: (Mean difference/standard error of mean difference)=significant indicated by *, or = highly significant indicated by **. [Degrees of freedom for testing significance of mean differences = (n - 1)].

Here E is the estimated average catch in the 22 tilted gages, corresponding to any average catch per storm (X) in the vertical gages. To show the relative precision of this predicting equation, its correlation-coefficient (r) is +0.9980, and the standard error of the predicted value E, for any storm which was not included in the regression-sample of 65 storms [1], varies from about 8.5 per cent for storms approximating the logarithmic mean of the recorded storms, up to about 8.9 per cent for the smallest and largest recorded storms (0.055 inch and 16.980 inches in the vertical gages). Strictly speaking, these statistics apply only to the 22 gage-locations in this particular

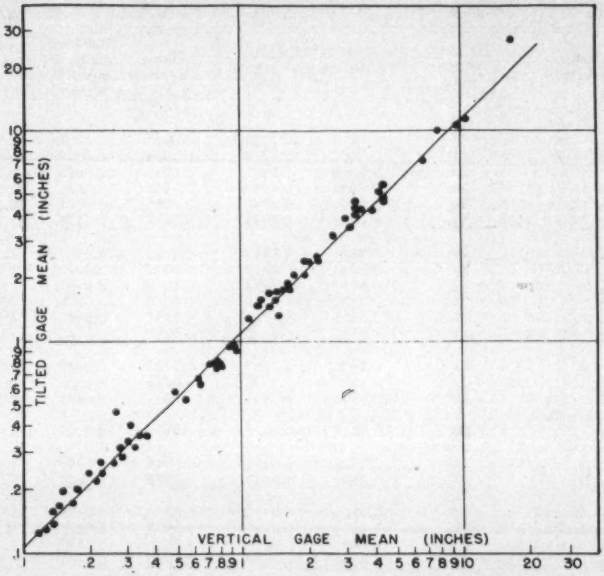

Fig. 2--Relationship between mean storm-catch of tilted and vertical gages

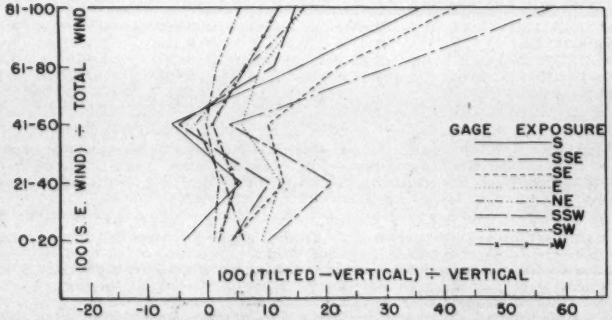

Fig. 3--Relation of percentage-difference in gage-catch to percentage of storm-wind coming from south

watershed, and the equation can be very useful in estimating the rainfall which would have been caught in the tilted gages during any period in which only vertical gages were in use.

The rather large standard error calculated for the data of Figure 2 indicates the possibility that other factors besides measurement-error may have limited the accuracy of the predicting equation. Accordingly, the direction of wind during storms and of gage-exposure were selected for preliminary analysis.

This problem was simplified by the fact that, at least during storm-periods, the predominant wind-directions were southeast or northwest, with little wind from other directions. Therefore, it was possible to classify storms simply according to the percentages of storm-time during which the wind came from the southeast. The differences between vertical and tilted gages were then grouped according to direction of gage-exposure, and the average difference for each group plotted against the wind-direction values. Figure 3 presents these curves.

It will be noted that for southerly exposed gages the difference is minus or very low for a northerly wind and very strongly positive for a wind from the south. For an east or west exposure there is little difference between tilted and vertical gages whether the wind is northerly or southerly.

Conclusions--On a small watershed of rough and steep topography, the use of tilted rain-gages provided data on precipitation which were usually higher than records obtained in vertical gages. The excess catch in tilted gages usually became greater with increasing size of storm.

The magnitude of differences between paired vertical and tilted gages appeared to be strongly affected by the prevailing direction of wind-movement. Tilted gages which faced directly into the wind showed the greatest excesses in catch as compared to vertical gages; gages facing away from the wind generally caught less rain than the vertical gages; and gages which were normal to the prevailing winds showed no significant differences in catch.

Tilted gages should be expected to provide a closer approach than vertical gages to the true volume of precipitation caught on a mountain watershed, with the reservation that enough gages must be installed to provide a truly representative sample of the various slopes and exposures existing in the drainage-area studied.

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AMERICAN GEOPHYSICAL UNION

TWENTY-FIFTH ANNUAL MEETING

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REPORTS AND PAPERS

Washington, D. C.
June 1, 1944

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REPORTS AND PAPERS, SECTION OF TERRESTRIAL MAGNETISM AND ELECTRICITY

THE GEOGRAPHIC INCIDENCE OF AURORA AND MAGNETIC DISTURBANCE, NORTHERN HEMISPHERE

E. H. Vestine

(Abstract)

The isochasms of FRITZ for the average of the 172-year period, 1700 to 1871, are tentatively revised and adjusted to an auroral-zone curve defined by geomagnetic data. In addition there are derived estimates of the frequency of aurora at the auroral zone and for the isochasms inside.

A compilation is made of data on auroral frequency for over 100 high-latitude stations operating since 1872. These include those of the First and Second International Polar Years, 1882-83 and 1932-33, and other miscellaneous years. The observed frequencies of aurora are reduced to a basis nearly independent of the seasonal variation in amount of sunlight with latitude, and roughly also for the influence of clouds on number of auroral observations.

Maps are presented showing the percentage of days per year on which aurora may be seen visually on clear, dark nights at various points in the Northern Hemisphere.

Near the auroral zone the frequency of aurora does not depend much on sunspot-cycle. Near the center of the auroral zone and in lower latitudes the frequency of visually observed aurora is much greater near sunspot-maximum than near sunspot-minimum.

Isolines of geomagnetic disturbances constructed for the Northern Hemisphere show close correspondence in general form with those for aurora.

Isochasms for the Southern Hemisphere and for the hourly frequency of aurora are in the course of preparation. The complete paper is published in the Journal of Terrestrial Magnetism and Atmospheric Electricity [v. 49, pp. 77-102, (1944)]

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RELATION OF THREE-HOUR-RANGE INDEX K TO AURORA SEEN AT ITHACA, NEW YORK

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Auroral data have been accumulated in the National Geographic Society-Cornell University study of aurora since 1938. In this paper these data for the years 1938-41 have been studied for four observers and also for auroras at Ithaca during 1938-42. Our cooperating observers assigned ratings to the aurora of each hour largely on the basis of maximum brightness, using O, G, I, II, III, IV, to cover the range from no aurora to maximum. The observations of JACK GRANT (Orillia, Ontario), CYRUS J. FERNALD (Wilton, Maine), the Milwaukee Astronomical Society, and those of myself and others in Ithaca were combined for three-hour periods, the averaging process giving ten rating-indices called A′. The data are shown in the upper half of Figure 1. The rating-indices for Ithaca (lower half of Fig. 1) were gradually developed and then applied as uniformly as possible to the whole series of observations. These indices represent the maximum in a three-hour period (dividing the Greenwich day as for K's). The ratings are as follows:

Index	Ithaca only	Three other observers
0	No aurora or very weak glow	No aurora
1	A glow, or possibly trace of an arc	Very faint
2	A good arc, elevation 10°-20°, or very bright glow	Faint
3	Very bright arc or faint rays	. . . . .
4	Ray-forms up to elevation 42°	Medium
5	Ray-forms up to elevation of about 70°	. . . . .
6	Ray-forms to zenith	Bright
7	A corona or aurora 20° south of zenith	. . . . .
8	Aurora 45° above southern horizon	Very bright
9	Aurora 15°- 0° above southern horizon	Extra bright

OBSERVATIONS IN EACH CLASS

	0	1	2	3	4	5	6	7	8	9	SUM
K	167	248	260	256	206	129	60	21	8	8	1363
A'	359	303	210	120	186	92	64	17	9	3	
	4 OBSERVERS										
K	59	158	175	159	117	73	43	15	3	3	805
A'	170	327	134	34	54	32	31	15	7	1	
	1 OBSERVER										

Fig. 1--Distribution used for classes of aurora and magnetic data

AURORA A \ K	0	1	2	3	4	5	6	7	8	9
9										3 1
8	Very Bright		Elev. 135°					1 5	4 1	4 1
7			Corona		1 0	2 3	6 9	7 2	1 0	0 1
6	Bright			1 1	10 1	20 9	21 12	9 6	2 2	1 0
5				9 2	18 4	42 15	19 10	3 1	1 0	
4			15 0	46 11	77 20	36 15	11 7	1 1	Med.	Rays
3		4 2	15 1	52 7	33 13	13 8	3 3			
2	3 3	26 9	62 27	61 41	42 35	16 17	0 2		Faint	Arc
1	31 27	96 89	94 96	57 71	25 38	0 6			V. F.	Glow
0	133 29	122 58	74 51	30 26	0 6					
	0	1	2	3	4	5	6	7	8	9

K FIGURES

Fig. 2--Number of pairs of aurora and magnetic data in each class (upper data in each box for four observers, lower data for Ithaca)

Thus the southern extent of the aurora is an important factor as is the form of the aurora. Both rating-systems are general auroral-indices since it is almost certain that the numbers assigned by our observers represent more the magnitude of an aurora than its brightness only.

Each set of data was paired with the K-figures for corresponding times. These paired data are plotted in Figure 2, in which those for Ithaca are the lower ones in each box. This figure shows the number of times that each combination of A' and K occurred. An obvious correlation is shown, the coefficient of correlation being about 0.8.

These two-dimensional arrays were equalized in K, that is, each K-column was made to contain 100 observations distributed according to the natural distribution of the number of auroras in each class. The percentage of auroras of given size was then taken for the various K's and plotted for each aurora class in Figure 3. Thus Figure 3 is to be read from left to right only as each auroral class is plotted separately. The percentage is plotted as a vertical line up to 40 per cent. When the percentage exceeds 40 per cent the line runs to 40 per cent and then another line is run from the base-line so the sum of these two equal the percentage.

The Ithaca data are on the right giving a comparison of two general methods of rating auroras.

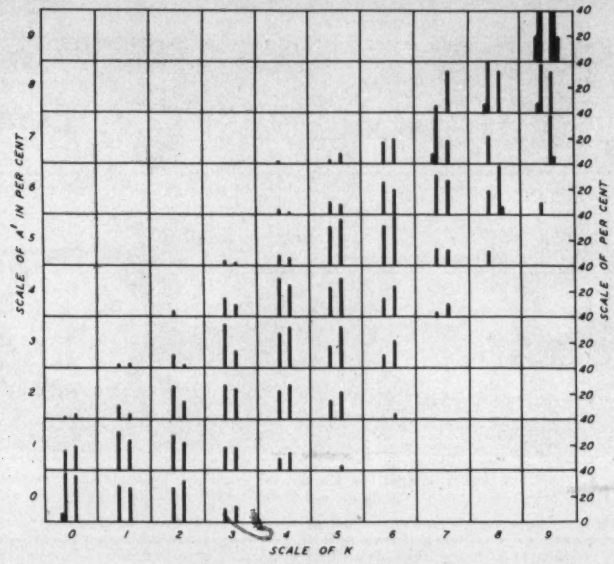

Fig. 3--Percentage of auroras of each size occurring for each size of K (data at left for four observers, at right for Ithaca)

Consider the Ithaca data. When no auroras are seen the K-figure is 0 or 1 about 60 per cent of the time, for only four per cent is it as great as K = 4, and never is K = 5. For Class 3, a strong arc, K is 4 or 5 in 63 per cent of the cases, occasionally K is 1 or 2, but K is 6 in 20 per cent of the cases. For Class 5, rays above the Pole Star, K is 5 or 6 during 80 per cent of the time. For K = 7, 8, or 9, there are too few observations to get a good distribution.

The data for four observers shows approximately similar distribution, but this classification results in assigning auroral character-numbers about one unit higher than the numbers assigned at Ithaca.

Both systems of classification used above seem to be equally good and show that there is a good correlation between the auroras seen in geomagnetic latitude 52°-56° with the Cheltenham K-figure. It seems desirable to try similar relations for shorter time-intervals and also for single aspects of the aurora.

We propose to make this study by punching the appropriate data on Hollerith cards and then sorting and tabulating by machines. The following data will be placed on the cards, preferably for hour or half-hour periods, rather than three-hour periods.

Punched-card analysis of auroral data

Serial No.	Intensity	Spectrum
Time of beginning of period	Duration	Photoelectric
Station	Principal form	Times of changes in form
K, Cheltenham	Sequence	Peak of display
K, Agincourt	Elevation	Multiple arcs, bands, etc.
Moonlight	Motion, east-west, north-south	Special forms
Twilight	Pulsations, presence and rate	

Column for each form to show importance, red border or all red.

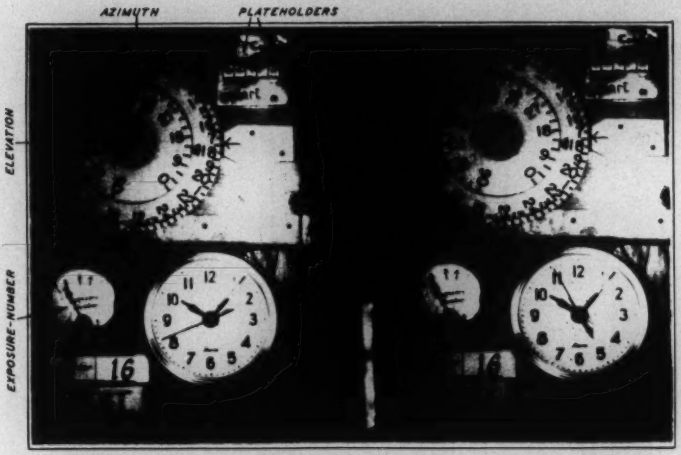

Fig. 4--Secretary camera data for one descriptive picture (left for beginning of exposure, right for end of exposure)

A coding arrangement has been worked out so most important chronological aspects can be used. The work of putting our original data from several observers in homogeneous form is so great that it seems advisable to go through these data once taking out all important items. It seems likely that observations from several observers within 100- to 200-mile radius can be combined to describe one time-interval. Observations from several observers should differ only in brightness and southern extent. The data for southern extent will be entered as geomagnetic latitude so the differences between observers disappears. (Suggestions and criticisms on this proposed study using punched cards are most welcome.)

The auroral observation is being continued at Ithaca and observations are made at about 15 other stations. Taking of data is made as automatic as possible. We have installed a secretary camera to photograph the data applying to height-measurement photographs as they are taken (see Fig. 4). Two exposures on 35-mm film gives us time of beginning and end, exposure-number, plateholders at Ithaca and Colgate, azimuth, elevation, and approximate intensity.

Two patrol spectrographs are run nightly. The one with lens F/1.65 exposes for four to eight hours while the F/.8 lens gives exposures of about one hour on a moving plate (see Fig. 5).

The photoelectric recorder has been run since 1941, giving fine records on all of the aurora

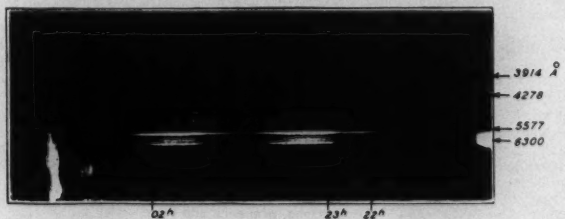

Fig. 5--Patrol spectrogram F/.8, September 28, 1943, for same night as Figure 6

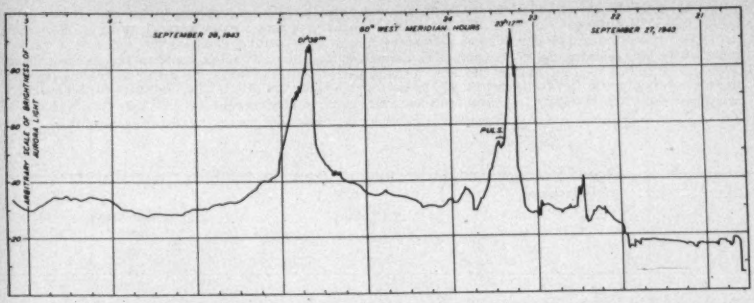

Fig. 6--Photoelectric record of auroral light, September 27-28, 1943, showing peaks

September 17-20, 1941. It now seems clear that certain types of record occur repeatedly and sharp peaks coincide with world-wide magnetic disturbances. This photoelectric recording seems so valuable that a whole new recorder is being built. The photocell, RCA 1P21, is on hand, and the amplifier and power-supply are being designed. A wider-range recorder is scheduled for delivery by July 1, 1944. The record of September 27, 1943 is shown in Figure 6.

Single photographs of the usual type are so unsatisfactory for statistical and chronological purposes that a simple all-sky camera has been set up. A movie camera photographs the sky-image in a convex mirror having an aluminized surface. The optical system is far from perfect but still very useful. The camera is electrically controlled. It seems entirely possible to turn this camera on when the photoelectric indication reaches a predetermined value.

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CURIOSITIES OF MAGNETOGRAPHS

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Most of the magnetographs operated by the United States Coast and Geodetic Survey utilize well-established methods of recording. From time to time various innovations have been introduced some of which have led to interesting features in the resulting records. This paper deals primarily with the interpretation of such features.

It may be of interest to note the general arrangement of instruments in the Eschenhagen magnetograph. The variometers are in a line running magnetically east and west--that is, in the magnetic prime-vertical. The lamp is nearly in the same line, but sufficiently away from it so that none of the variometers is screened by another one; and the recorder is near the lamp, on the other side of the same line [see 1 of "References" at end of paper]. Each variometer has a weak lens to focus on the drum an image of the light-source.

In addition, the recorder usually has a short-focus cylindrical lens running the full length of the drum so that any source of light at an appreciable distance is focused to a fine line on the drum.

This type of recorder has generally a set of adjustable tabs on an axle, arranged to drop down after every 20 mm of motion of drum, obscuring the several base-lines and making automatic time-marks. This system of marking time leaves much to be desired. Through the ingenious efforts of the Section of Operations several improved methods have been worked out. One of these was tried for a few years at Tucson (see Fig. 1). It entailed the use of a variable-width vertical slit in front of a horizontal filament. A device operating from a pendulum clock widened the slit for a brief interval at the end of every hour [2].

On the whole, this was a definite improvement over the former system, though now it has given place to a still different scheme. But the optical features of this set-up present several interesting aspects. It was no longer considered necessary to use a cylindrical lens, as the spots were very small both horizontally and vertically. One drawback was that an insect could interrupt the record by remaining in a certain spot on the slit. (There were instances when the different traces were interrupted singly at different times as an insect moved along the slit.) The omission of the cylindrical lens made it practically impossible to keep the various spots accurately in line; this was not a

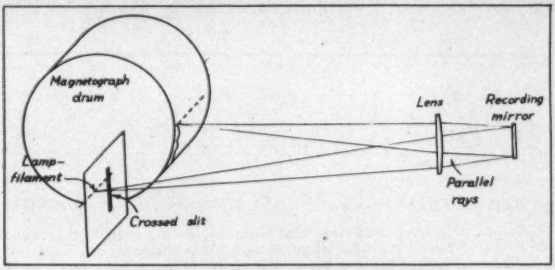

Fig. 1--Magnetograph without cylindrical lens

serious matter since the time-marks in each trace were used for scaling that trace only.

Note that with this system there is some stray light going through the slit; the effect of this is that each spot is in reality a faint image of the slit, lying along the paper roughly parallel to the time-axis, with a bright spot at the point corresponding to the filament. Ordinarily this point is the only part bright enough to leave a record, but if a translucent body such as a moth's wing gets in front of some other part of the slit, there may be enough light concentrated there to provide an extra trace, displaced along the time-axis from the regular trace. Figure 2 shows this effect faintly in the H-trace. It also shows what happens in this system when the driving clock stops. Each spot is accompanied as it slowly moves back and forth in its track, by the faint stray image, and the accumulation of light-energy is sufficient to show the whole slit in this case. A modification of this system subsequently adopted at Cheltenham includes the cylindrical lens and has been working with perfect satisfaction for several years. A convenient feature of the use of the cylindrical lens is that it keeps the parallax (or displacement of spots along the time-axis) small. The elimination of parallax is then chiefly dependent on getting the ray-paths through the centers of the different variometer-lenses all in the same plane [3].

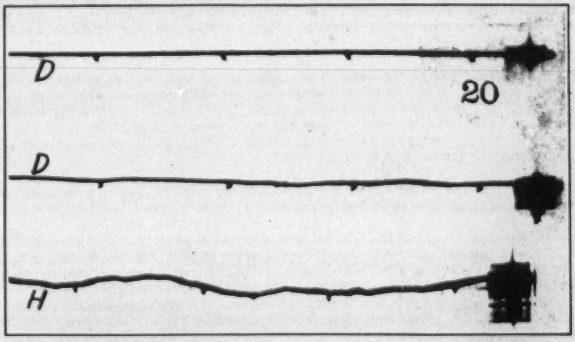

Fig. 2--Portion of magnetogram produced by the scheme shown in Figure 1, illustrating effects obtained during failure of driving clock; record from Tucson, September 25, 1937

Another modification is to insert a collector-lens near the lamp, so that the light-source is within the principal focus of the collector-lens. Such a lens has two chief effects--it alters the effective distance from the source to the variometer, altering the focusing adjustment, and it increases the amount of light available for the spot. The former effect could be utilized as a preliminary test to determine how much adjustment would be needed to correct faulty focusing of the spots.

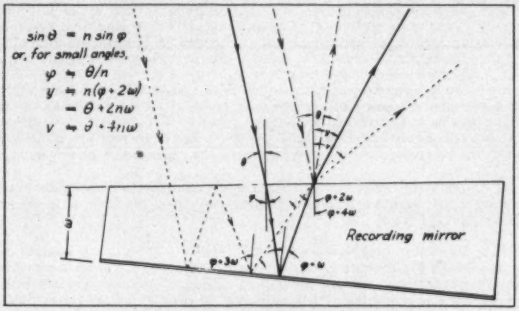

Fig. 3--Formation of ghost traces

Figure 3 shows another aspect of the problem of producing clear records--the commonest source of ghost-traces. The recording mirrors are generally made with great care, so that the two faces are parallel within very close limits, but it is instructive to note the effect of the slight residual angle (greatly exaggerated here). One of the ray-paths contributing to the regular spot is shown by the heavy line. There are, of course, rays exactly like this entering the mirror at many points along its surface. Choosing another of these (dotted line) we note that a fraction of the light is reflected inward at the front surface so as to form a weak companion to the main ray; and a similar companion is provided by a third ray. The three sets of rays thus produced give the main spot and two ghosts. The spacing of the ghosts, for a D-variometer, is easily computed from the scale-value; obviously a very minute non-parallelism of the faces will result in ghosts, but with circular mirrors they can be rendered innocuous by orienting the mirror so that they fall in a line parallel to the time-axis, since the customary cylindrical lens will then bring them into coincidence with the main spot.

A related problem is that of producing a reserve-spot that will record, for example, the reduced values of H prevailing during magnetic storms. A common method of doing this is to equip the recording magnet-system with two mirrors. They may be separate mirrors situated above one another [4] or they may be different faces of a single prismatic front-surface mirror [5]. In

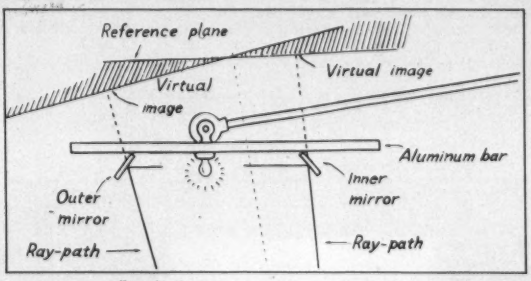

Fig. 4--Reserve-spots by mirror method

either case, the angle between the two faces must be equal to the desired "reserve-distance" multiplied by the angular scale-value. Another scheme requires only a single recording mirror but uses in effect two sources of light, each producing a separate spot. One method of accomplishing this is to shield the light so that its rays do not fall directly on the variometers, but are instead reflected toward them from two mirrors. In this instance the mirrors were of the alloy known as Stellite. Figure 4 shows parts of the ray-paths for one variometer; those for the other variometers would be slightly displaced from the ones shown. Normally only one of the two ray-paths shown is used, serving for both the trace and the base-line. This scheme is still in use at Sitka and is entirely successful. However, some difficulty was experienced when it was first set up, and it was operated for a time with the H-trace and H base-line produced from different mirrors. In processing the records, it was important to know this, since it meant that every time the lamp was adjusted, the H base-line value underwent a change. Analysis of the geometry of the scheme shows that such a change will occur unless the adjustment constitutes mere translation of the two virtual images of the source. If the adjustment is such as to rotate the images about a point in the shaded area, the trace and base-line would shift in opposite directions, otherwise (the usual case) they would move in the same direction by probably different amounts. If the center of rotation were sufficiently close to the intersection of the reference-planes, the motion of the spots would be negligibly small.

One further point may be of interest. The usual methods of keeping the magnet of an H-variometer in the magnetic prime-vertical depend primarily upon the torsion in the suspending fiber, or for a bifilar, upon gravity.

It has occurred to the writer that an alternative scheme would be to use control-magnets to counteract the mean value of the Earth's horizontal field. By using a combination of magnets with different temperature-coefficients, perhaps the opposing field could be kept independent of temperature. The system of control-magnets could be arranged to provide an artificial field in the prime vertical, and the recording magnet could then operate exactly as in an ordinary D-variometer. Now, I have no doubt that this has been tried; in fact KOHLRAUSCH [6] discusses something very much like it, and MASCART [7] mentions his proposal. However, it seems possible that no one has tried it in recent years with the newer magnet-steels which afford greater variety in properties.

In concluding these remarks on the curious effects of various innovations in variometer-operation, the writer wishes to express his appreciation of the generous technical assistance and advice received from H. E. McCOMB and Dr. H. HERBERT HOWE, who first noted some of the effects discussed, and also of the assistance received from Mrs. U. Y. POTTER in the preparation of some of the illustrations for this paper.

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ANALYSIS OF MAGNETOMETER-DEFLECTIONS

Abstract--The usual set of deflections on a magnetometer contains a greater number of deflections than the minimum number necessary to determine the quantities involved. Thus, there are certain relations which exist among the different deflections, excepting only the effect of errors of observation and changes of the Earth's field. Knowledge of these relations makes it possible to detect blunders and to estimate the quality of observations. The complete paper, of which the matter following is only a part, analyzes these relations.

Observations of horizontal intensity by the method of GAUSS involve two kinds of observations, that is, oscillations and deflections. In the deflections, observations are made under varying conditions to eliminate various sorts of errors resulting from imperfections in the construction of the instrument. However, it is customary to make a greater number of observations than the minimum number needed; hence, there are certain relations that should exist among the deflections, excepting only the effect of change of D or H during the observations, and excepting experimental error in the measurements. As with any instrument, familiarity with these relations serves several purposes: (1) They make it possible to identify unquestionably gross blunders in reading the circle; (2) they may serve to give an estimate of the performance of different instruments and the ability of different observers.

With many instruments, however, the expected relation is simply that consecutive readings should agree. With magnetometer-deflections, however, the relations are more complicated, and can be discovered only by somewhat extensive analysis. I do not know whether the complete set of relations has been published; at any rate, the current investigation should serve a useful purpose.

It is not feasible in the time available to attempt to derive these relations. It seems preferable, rather, to describe them in some detail, and give examples of their use.

When used for deflections, the magnetometer has a "short magnet" suspended by a fiber, and a "long magnet" mounted magnetically east or west of it on a deflection-bar. On the bar are stops of some sort to fix the position of the long magnet. The stops are placed in pairs (from two to five pairs), the stops of each pair being at (nominally) the same distance from the short magnet. The distance between the centers of the magnets is supposed to be the same whether the magnet is to the east or to the west of the short magnet, and whether the north end of the long magnet is to the east or to the west--but, of course, this is not precisely achieved. Since the deflection observed is quite sensitive to small change of deflection-distance, the four deflections observed for one distance are not, in fact, equal. Except for the effect of play in the stops, the difference of deflection-distance according as the north end of the long magnet is east or west should be the same for each set, depending only upon the distance between the magnetic center of the magnet and the groove used to mark its center; on the other hand, the relation of the deflection-distance for deflector east and deflector west is different for each set, depending upon the leveling of the instrument and the warping of the magnet-house.

In the following discussion, it is assumed that any play in the stops is always taken up by pushing equally hard in a specified direction and that, as a result of this, the amount by which the magnetic center of the magnet is displaced by reversal of the magnet is the same irrespective of which stop is used. The distance between the east and west stops will have been measured, and it is assumed that this is twice the distance between the magnetic centers of the magnets, when this is averaged over the four deflections.

(I) Deflections at one distance--The following notation is used: EW represents the circle-reading when the deflector is to the east of the short magnet, with the north end of the deflector to the west; etc. There are four deflections, and hence four circle-readings.

There are also four quantities to be determined: (1) H/M (strictly, it is B/M); (2) the circle-reading corresponding to the undeflected position of the magnet; (3) difference of mean distance when deflector is east and distance when deflector is west; (4) the amount the magnetic center of the magnet is moved when the magnet is turned end for end.

Since there are four observations and four quantities to be determined, there are no relations among the four readings. It may be noted that there are really two major distances involved, the distances between the stops and the short magnet; but we have measured the sum of the distances, leaving only the difference, as (3) of the preceding paragraph.

(II) Deflections at two distances--There are four additional deflections, but only one additional quantity to be determined. Since the observations at the two distances are intermingled, quantities (1), (2), and (4) of the preceding section are the same, only (3) being different. Hence, among the eight deflections there must be three relations.

These are as follows: (a) H/M should be the same as derived from the two distances; (b) the mean circle-reading for one distance should be the same as for the other--this may in practice be computed more readily by taking horizontal differences and adding them; (c) the quantity (EE - WE + EW - WW) for the one distance should stand in the following ratio to that for the other distance: ($r^4 \cos u / R^4 \cos U$), where R and U refer to the large distance and r and u to the small distance. For many magnetometers, u and U are small enough so that ($\cos u / \cos U$) may be replaced by unity for the accuracy required, the ratio becoming then merely (r^4/R^4), which depends upon the magnetometer alone. If r = 30 cm and R = 40 cm, (R^4/r^4) is about 3.2.

(III) Deflections at three or more distances--There will be three additional relations for each additional distance, the same as for the second distance.

(IV) Deflections at one distance, at two different times--There will be eight deflections; in general, the quantities described under (1), (2), and (3) above will be different, while (4) will be the same for each time; hence, there should be one relation among the eight deflections. This relation is as follows: So long as H has not changed by more than a few per cent, (EE - WE + EW - WW) is the same for each set. If H changes considerably, then this quantity varies inversely as H cos u.

(V) Deflections at two distances, at two different times--It can be shown that there should be eight relations among the 16 circle-readings. Three are given in (II) for each time, making a total of six; one is given under (IV), for one distance only (the corresponding one for the other distance is not independent of the two under (II-c); so that there is one additional relation. This relation means that as the position of the short magnet is changed by releveling there is a relation among the changes in the four distances involved.

This relation is, perhaps, the easiest to use, but it is the hardest to describe. First, compute the difference (EE - EW + WW - WE) for each of the four groups of deflections. (EE - EW) is simply 2u for deflector east; (WE - WW) is 2u for deflector west; thus we compute ($2u_E - 2u_W$). For many magnetometers, the ratio of this quantity for the short distance to the same quantity for the long distance is simply the quantity ($R^4 \cos U / r^4 \cos u$) discussed in (II-c), and which for certain magnetometers has the value 3.2 If this were true in general, we would have an additional condition when just one set at two distances is made; it involves the assumption that the stops on the east deflection-bar are the same distance apart as are those on the west bar.

The more general relation, which must be used for some instruments, is that ($2u_E - 2u_W$) for the short distance when divided by the above quantity should differ from ($2u_E - 2u_W$) for the long distance by a constant.

(VI) Two distances erect and two distances inverted--If the inverted deflections follow the erect deflections, we have an additional condition, as follows: The mean circle-reading erect should equal the mean circle-reading inverted if the short magnet is not inverted; if it is inverted, they should differ by (E - I). If (E - I) for the short magnet is not known from any other source, this does not give us a condition on a single set; but it does give a relation among different sets.

Application of these rules--In order to make it feasible to apply these checks, the computations must be made in the most efficient manner possible. In many cases, it will suffice to omit the seconds from consideration, taking into account only the minutes.

It is also necessary to know to what accuracy one may actually expect constancy in a quantity which should be constant. This depends upon the value of the deflection-angle, the amount of magnetic disturbance, the length of time covered by the observations, as well as upon the condition of the instrument and the ability of the observer. It appears that, at least for many cases, constancy within about 2′ may be expected for a quantity that involves the sum or difference of eight circle-readings. This applies to the relations given under (IV) and (II-b). The relations under (II-c) and

(V) involve four circle-readings and four others reduced to about one-third; hence they may be expected to be fulfilled within about 1'.5.

For relation (II-a), involving the equality of values of (H/M) we have for each distance four circle-readings, or eight in all; but there is a factor of 1/4, so that we should expect agreement corresponding to an uncertainty of 0'.5 in u. This corresponds to an agreement of the two values of log (H/M) within 0.00006 cot u. If u is about 6°, this would mean agreement of log (H/M) within about 0.00060. It may be noted, however, that if the constant of the magnetometer is not well determined, there may be a constant difference between the two values of (H/M) superimposed upon this random difference.

[It is expected that the complete paper will be published in the Journal of Terrestrial Magnetism and Atmospheric Electricity.]

U. S. Coast and Geodetic Survey,
Washington 25, D. C.

A STUDY OF THE SUSCEPTIBILITY OF SEDIMENTS

H. Wayne Hoylman and H. A. Durbin

(Abstract)--There is discussed a portion of the experimental work undertaken in studying the susceptibility-behavior of sedimentary cuttings obtained from bore-holes. A rather elaborate system of heat-treatment (employing temperatures well above the Curie point) of the cuttings was developed and their susceptibilities were determined at various stages during the treatment. In general, it was found that many original sediments - principally shales - with little or no susceptibility became strongly magnetic by a proper heat-treatment. As a result of the work it became apparent that it is possible to use the susceptibility-values after heat-treatment to make stratigraphic correlations within a geological province.

Introduction--A number of years ago in the field of geophysics there was considerable discussion about the magnetic properties of the sediments. Some published articles reported magnetic anomalies, as detected by the magnetometer, were coming from sedimentary beds of high magnetic susceptibility buried at depths greater than 1,000 feet.

Theoretical analysis of the problem shows that a magnetic horizon would have to be not only quite thick but have a rather large susceptibility-contrast, if an anomaly is to be produced which would be detectable by the present type of field-instrument. For example, if a magnetic horizon is assumed that is 2,000 feet thick and which is buried 3,000 feet below the surface of the ground at the apex and 7,000 on the flanks, it must have a susceptibility-contrast of 500×10^{-6} CGS units to produce an anomaly of 20 gammas. Although several variables enter into this type of problem the one selected as the most important to investigate was the susceptibility-contrasts of sediments.

Investigation of the available literature shows that the susceptibility of the rock-forming minerals varies widely. Furthermore, magnetite, by reason of its relatively large susceptibility and wide distribution is easily the most important ferro-magnetic mineral. Actually the susceptibility of a rock is generally determined solely by its percentage of magnetite. Unfortunately, the published results show that the susceptibility of this mineral has a wide range which is dependent not only upon the specimen itself but also upon the intensity of the magnetizing field. From SLICHTER'S work it can be seen that the maximum susceptibility of magnetite occurs in fields of 10 to 20 oersteds. Most of the published results of susceptibility-measurements of rocks do not show what field-strength was used so that contrasts of values are meaningless.

Inasmuch as we were desirous of supplementing published information it was decided to build a device for measuring the magnetic susceptibility of rock-specimens. This magnetic characteristic is defined as follows:

$$K = (I/H)$$

where $I = (B - H)/4\pi$, with B = flux-density in Gauss, H = magnetizing force in oersteds, and I = intensity of magnetization.

Susceptibility-meter -- The instrument used was designed by V. VACQUIER and is essentially an inductance-bridge. The circuit-diagram is shown in Figure 1. The dashed rectangles, on this diagram, indicate the boxes into which the various parts of the bridge are segregated. The inductive arms of the bridge are contained in the lower box B_1. Included, also, in this box is a decade-resistor of 0.1 ohm per step and a slide-wire for adjusting the resistance-balance. The resistance-arms of two 10,000-ohm resistors of the bridge are contained in B_2 which is a shielded box. The common junction of the resistors is connected by a shielded cable to a three-stage amplifier A, the output of which operates a Leeds and Northrup vibration-galvanometer G. The bridge is supplied with a 60-cycle alternating current via the insulating transformer to T.

Coils C_1 and C_2 are solenoids of 7,500 turns wound on bakelite spools and designed to receive specimens to be measured. They are carefully matched for inductance. M_1 and M_2 are identical variable inductors. Each one consists of a pair of pancake coils, one of which is fixed while the other one rotates on an arm. A very nonlinear characteristic is thereby achieved which permits a wide range of measurement.

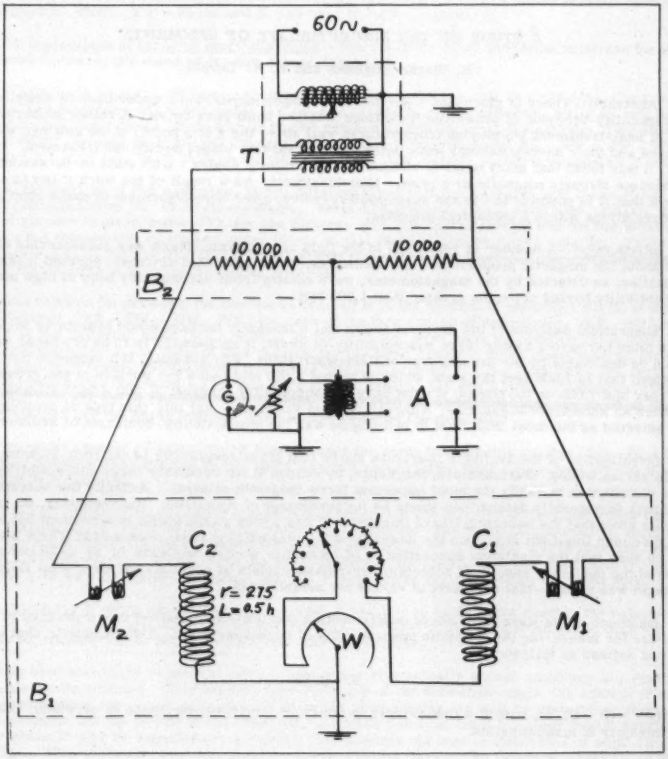


Fig. 1--Diagram of susceptibility-meter

To operate the meter, the dial of the variable inductor M_2 is first set on one end of the graduations with no specimen in either coil. The bridge is then balanced by manipulating the slide-wire W and the inductor M_1. Next the specimen is inserted into the coil C_2 and the bridge balanced with inductor M_2. The reading on the dial of this inductor is proportional to the susceptibility. During operation it is advisable to check the zero of the instrument about every five minutes. This is done by removing the specimen, resetting M_2 on its original value and balancing the bridge by slight adjustments of M_1 providing the zero has drifted.

The calibration of the dial of the inductor M_2 is accomplished by balancing the bridge with standard substances in the coil C_2. Actually, a test-tube containing a known weight of a paramagnetic compound is inserted in coil C_2 and the bridge is balanced with M_2. The reading on the dial of M_2 constitutes the first point on the calibration-curve. The test-tube is then removed and the bridge is balanced with the variable inductor M_1. This procedure is repeated until the whole range on the dial is used.

Inasmuch as there is some variation of the magnetic field in the solenoids, the amount of each sample should occupy essentially the same volume if accurate comparisons are required.

The purpose of coil C_1 is two-fold: First, it makes the apparatus astatic to external electromagnetic disturbances; second, it increases the range of the instrument. Obviously standard specimens may be inserted into C_1 to balance part of the effect of an unknown sample of C_2 for the case when the balance is beyond the range of the inductor M_2.

Measurements of original samples--Cuttings from bore-holes were obtained from Pennsylvania, Illinois, Indiana, Oklahoma, and Texas. They were ground and passed through a 50-mesh sieve. A specimen was thoroughly mixed and then divided into three five-gram samples. The susceptibility of each was determined. If all were within ten per cent of one another the average was taken as the susceptibility of the specimen.

It was suspected that clays and shales were more magnetic than limestone so that the first work was with them. The susceptibilities of the various specimens were found to be as follows:

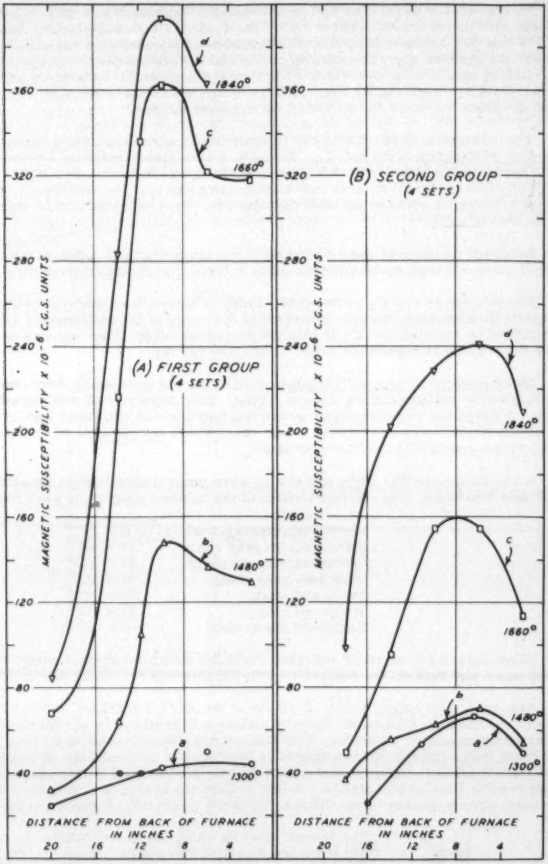
Illinois bluish gray shale	8×10^{-6}
Indiana bluish gray shale	12×10^{-6}
Pennsylvania gray shale	20×10^{-6}
Oklahoma gray shale	40×10^{-6}
Texas red shale	35×10^{-6}
Texas red clay	25×10^{-6}
Texas red sandy clay	5×10^{-6}

These values are so small that they could not affect the magnetometer unless they were exposed on or just beneath the surface on which magnetometer-observations were taken.

Heat-treatment experiments--Because of the work that DEAN, GOTTSCHALF, and DAVIS had done on the heating of hematite, thereby making a paramagnetic ore ferromagnetic, it was decided to heat-treat a number of shales. Identical samples were heated in various atmospheres and it was found that, although the susceptibility increased in all cases the increases were irregular. The first results made it apparent that a very carefully controlled treatment would be necessary if reliable results were to be obtained. It was evident the resultant susceptibility after treatment was dependent upon a number of conditions, the more important of which are as follows:

(1) Temperature at which sample is heated
(2) Position of sample in furnace
(3) Time-period for heating sample
(4) Atmosphere in which the sample was heated
(5) Preheating

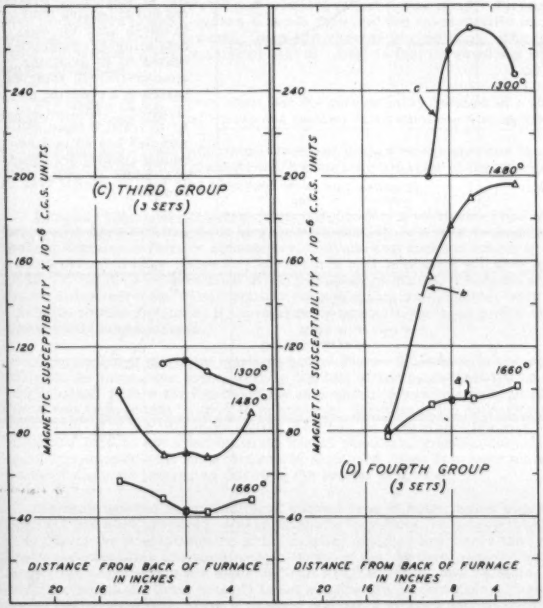
Plates have been prepared to show how these variables produced variations in the susceptibility of a uniform sample of a shale which had an original susceptibility of 8 to 10×10^{-6} CGS. Throughout this heat-treating work the samples were heated for a specific period of time and then were removed from the furnace and allowed to cool before the susceptibility was determined. Figure 2 shows how the susceptibility varies at different positions in the furnace when heated at a supposedly constant temperature for a 15-minute period. Because the increase in susceptibility is not uniform, it is inferred that the temperature is also not uniform.



The four curves comprising Figure 2-A show how the susceptibility varied with different temperatures for a set of samples which were enclosed in a stainless-steel box and exposed to furnace atmosphere. These curves show the necessity of not only carefully controlling the temperature of a sample but also its position within the furnace, if reproducible increases are to be obtained.

The family of curves shown by Figure 2-B are the results from heating an identical set of samples at the same positions within the furnace but they were not enclosed in the stainless-steel box. The heating took place in an oxidizing rather than furnace atmosphere. At 1,300°F the susceptibilities are essentially the same. At 1,480° and 1,660° the susceptibilities in Figure 2-B are approximately 50 per cent of those in Figure 2-A, while at 1,840° F the values in Figure 2-B are approximately 65 per cent of those in Figure 2-A.

Figs. 2--Variation in susceptibility due to various positions of sample in furnace when heated at a constant temperature for a 15-minute period: (A) First group of four sets, samples enclosed in a stainless-steel box and exposed to furnace atmosphere at positions and temperatures shown; (B) second group of four sets, samples exposed to heating coils in oxidizing atmosphere; (C) third group of three sets, samples exposed in a reducing atmosphere (charcoal has been added to fresh sample); (D) fourth group of three sets, samples exposed in a reducing atmosphere (charcoal has been added to preheated samples)



The family of curves in Figure 2-C show that there is little change in susceptibility when the samples are heated in a reducing atmosphere along with the addition of charcoal. The interesting thing here is that the largest susceptibilities are obtained from the lowest temperatures. This is just the reverse condition as shown in Figures 2-A and 2-B.

In Figure 2-D the samples were all preheated for 15 minutes in the furnace atmosphere, cooled, and charcoal added. The samples were then reheated but in a reducing atmosphere. These curves show not only that the susceptibility varies in the same manner as in Figure 2-C, but that the values are much larger as a result of preheating.

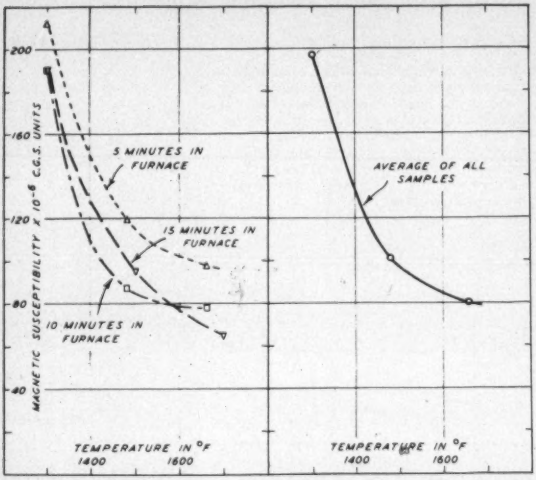


Fig. 3--Curves showing effect of time in furnace upon susceptibility [All samples were preheated for 15 minutes at respective temperatures (charcoal was added at beginning of second heating; at second heating the atmosphere was changed to one of reduction)]

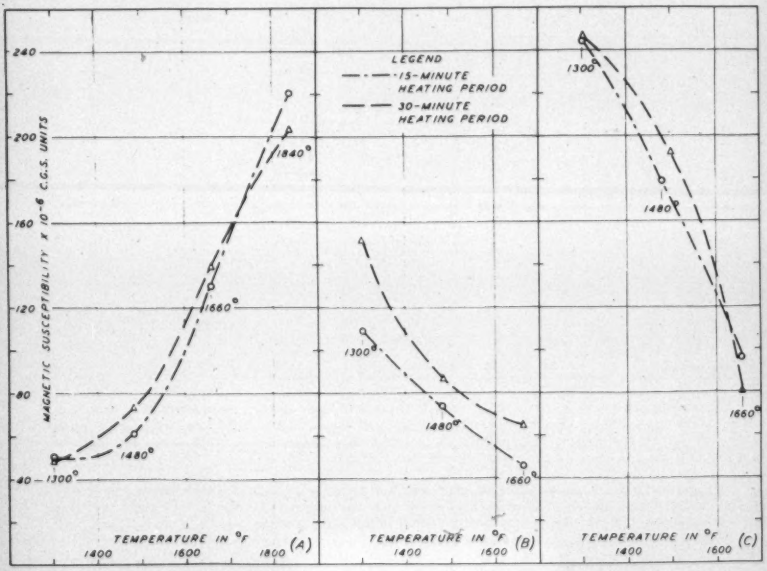


Fig. 4--Effects of different initial heating temperatures upon the susceptibility: (A) Samples heated in an oxidizing atmosphere; (B) samples heated in a reducing atmosphere (charcoal added to fresh sample; (C) samples heated in a reducing atmosphere (charcoal added to preheated samples)

From inspection of these curves it looks as though a shorter heating period would result in larger susceptibility; consequently, Figure 3 has been prepared to show how the time-variation affects the susceptibility. The samples used in these tests were all preheated for 15 minutes in furnace atmosphere at the respective temperature at which the second heating was to be made. Charcoal was added at the beginning of the second heating and the atmosphere was changed to one of reduction. The curves in Figures 3-A, 3-B, and 3-C all show the behavior of the susceptibility. It is apparent that after preheating, the largest susceptibility, irrespective of temperature is obtained during the first five minutes of heating.

Figure 4 is a continuation of the previous one as far as time of heating is concerned. The value of this Figure is to show that high temperatures give maximum susceptibility in an oxidizing atmosphere while low temperatures give the larger susceptibility in an atmosphere of reduction. It is also apparent from the results of Figures 3 and 4 that the susceptibility varies but little after the first five minutes.

Figure 5 has been prepared to show how the susceptibility will vary in three different atmospheres as the sample is heated and reheated at increasing temperatures. In Figure 5-A, when furnace atmosphere is used, curves A and B show that the susceptibility increases as the temperature increases. In curve C, however, there is a reverse of conditions. The rather surprising thing about the samples given an original heat of 1,840° is that the resultant susceptibility is the greatest of the groups.

In Figure 5-B the curves show that the susceptibility behaves in a similar manner to that in Figure 5-A except the final values are smaller in an oxidizing atmosphere.

In Figures 5-C and 5-D, where fresh and preheated samples are heated in a reducing atmosphere, the distinguishing characteristic is that the behavior of the susceptibility is just the reverse of what it is in an oxidizing atmosphere.

Results of the heat-treatment experiments--For a particular type of shale that is heat-treated the results show that to get the largest susceptibility in a most economic manner it is advisable to preheat samples in furnace atmosphere, then add charcoal and reheat in a reducing atmosphere for a short period of time. However, any form of heat-treatment will give some increase in susceptibility. From the heat-treatment of various kinds of shales, it became apparent that in order to get reproducible increases in susceptibility considerable experimental work would have to be done and a definite routine developed if correlation of magnetic horizons within sedimentary rocks is to be successfully accomplished.

Correlation of magnetic markers beds--Figure 6 has been prepared to show how the susceptibility varies throughout approximately 500 feet of sedimentary rocks after the samples have been heat treated. Before the treatment the susceptibility was so small, less than 10×10^{-6} CGS units, that it was impractical to show it on the logs. Samples of the cuttings were taken at five-foot intervals. The holes are two miles apart. Perhaps, at first glance the similarity of the susceptibility of the two logs is not apparent to the casual observer, however, to the trained eye there are, at least, five magnetic horizons that can be identified. Two have been marked as C_1 and C_2, however, the most apparent marker is that near the bottom of the log.

To show how the susceptibility of another type of shale varies with depth in a core drill-hole, Figure 7 has been prepared. These magnetic logs show the susceptibility before and after heating even though the susceptibilities of the original samples are larger than those on the Figure 6, the final susceptibilities are smaller by a factor of ten. In those rather short vertical sections of sediments the correlations are more difficult and, therefore, less reliable. Although there is a correlated horizon in the three holes it is not so apparent on this plate. However, on Figure 8 the horizon is easily identified. This is another method of plotting susceptibility against depth of hole and someways it is an advantage over the other but, in general, one is as satisfactory as the other.

Actually, in the area where this last work was done, there were ten core-holes available and a correlation was made for the entire group. Figure 9 shows the final results of the correlation before and after heat-treatment. As can be seen by the contour-maps the difference in elevation in this area is approximately 200 feet. There is also 60 feet of local structure shown between the small closure in the center of the map and the south edge of the contours. The structural difference between the two oil-wells in this same area was found to be over 400 feet at approximately 5,000 feet below the surface. In this area structures are known to increase in magnitude with depth.

Conclusion: Correlation of magnetic markers--From the data presented it is apparent that correlations can be made. However, in other areas the correlation-work was not successful. At the time when this work was done, which was a number of years ago, it was of considerable economic value. However, at the present time, the improvements in the various methods of well-logging makes this rather laborious method of logging uneconomical, except for special instances.

Acknowledgments--During the progress of this work many helpful suggestions were obtained from discussions with members of the magnetic section. Dr. W. P. RAND of the Geological Staff was particularly helpful. He not only worked with the writers in the early stages of the project but functioned in an advisory capacity throughout the work. He is credited with the fundamental idea of heat-treating samples.

The writers are deeply grateful to Dr. E. A. ECKHARDT not only for his encouragement of the work but for the permission for its publication.

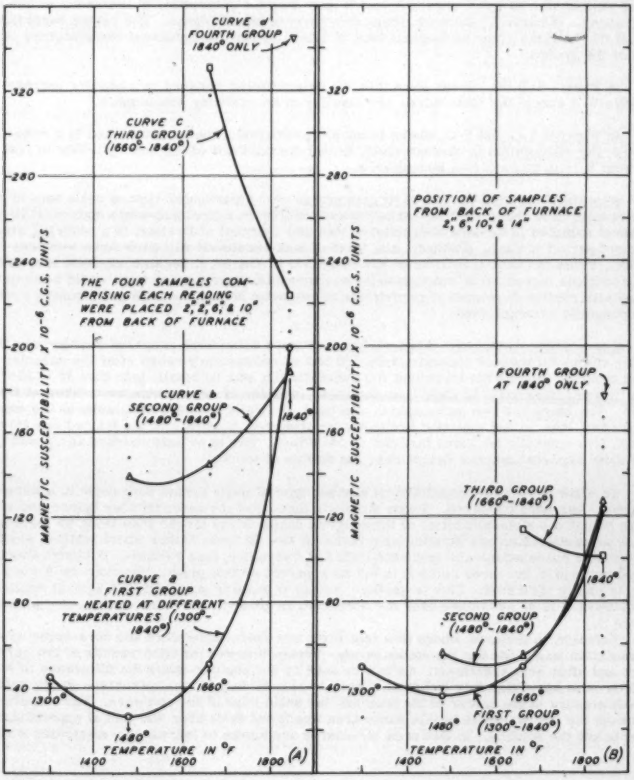


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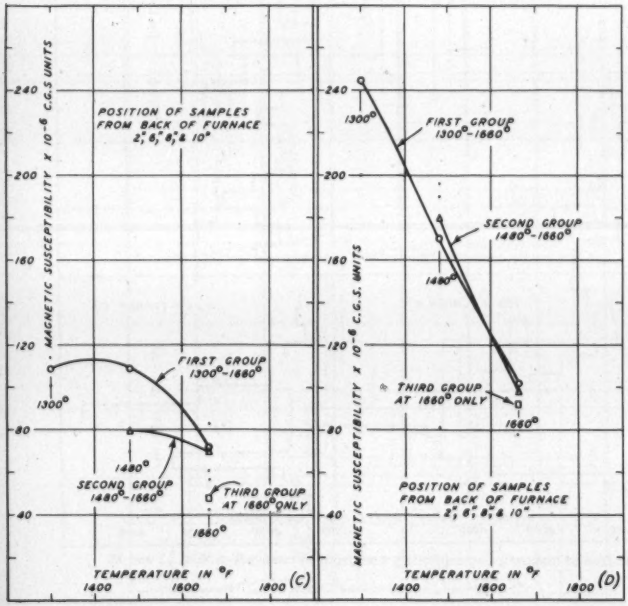
Fig. 5--Change in susceptibility due to repeated heating at increasing temperatures: (A) Samples heated in furnace atmosphere; (B) samples heated in an oxidizing atmosphere; (C) fresh samples heated in a reducing atmosphere (charcoal added); (D) preheated samples heated in a reducing atmosphere (charcoal added)



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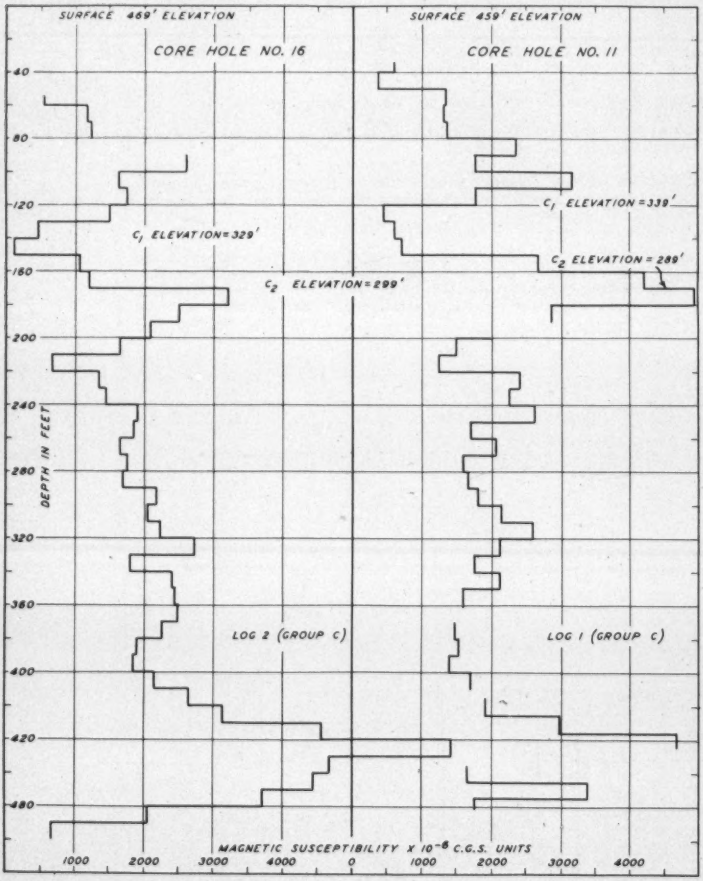

Fig. 6--Relation of magnetic susceptibility and depth in core-holes Nos. 11 and 16

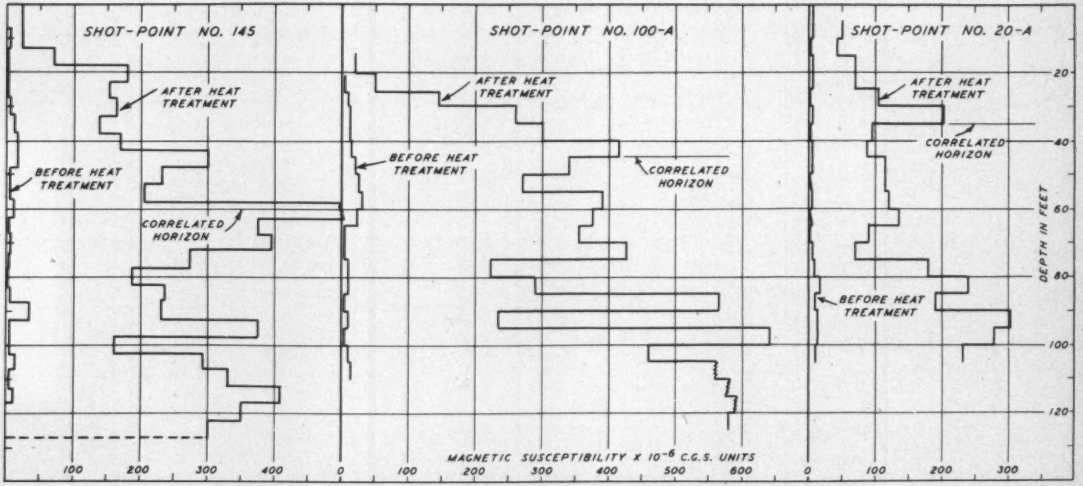

Fig. 7--Relation of magnetic susceptibility and depth for shot-points Nos. 145, 100A, and 20A

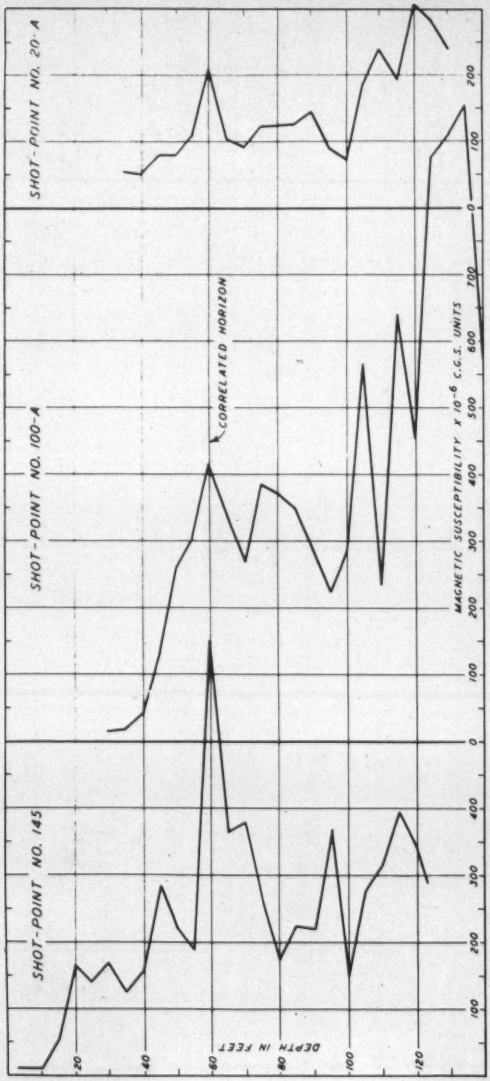

Fig. 8--Relation of magnetic susceptibility and depth for shot-points Nos. 145, 100A, and 20A for correlated horizon

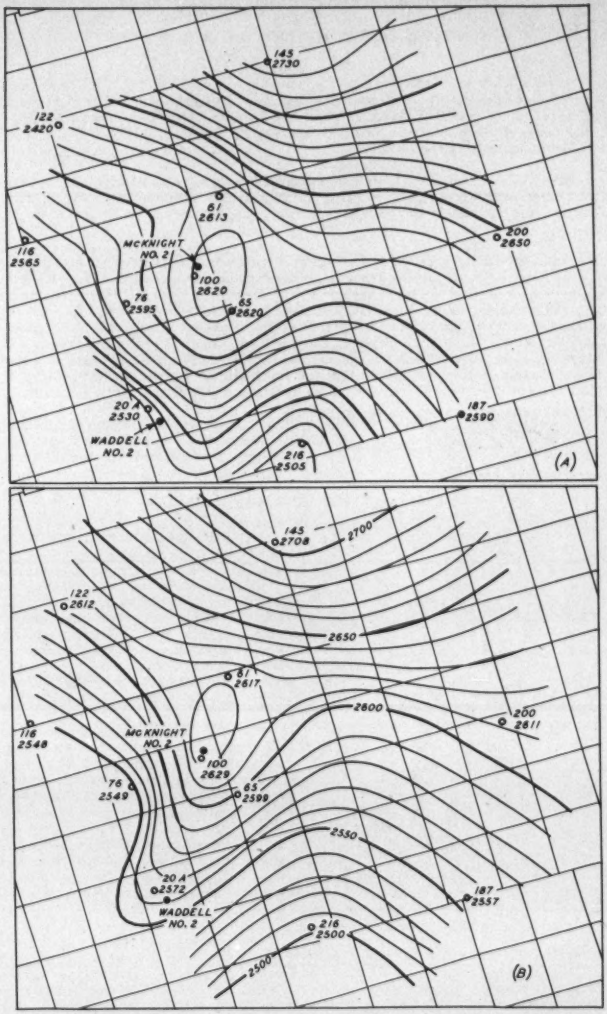

Fig. 9--Structure-contours based on susceptibility-determinations, (A) before heat treatment and (B) after heat treatment (shot-hole numbers indicated by upper figures and elevations in feet above sea-level by lower figures)

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A MAGNETIC SURVEY OF THE CANON CITY AREA

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The purpose of this paper is to present the results of a magnetic survey of the Canon City (Colorado) Area. The Canon City Area, as understood in this paper, lies between the 108° 10′ and 108° 20′ meridians of longitude and is bounded on the south and north by the 38° 20′ and 38° 30′ parallels of latitude, respectively.

Our survey was the first of its kind to be conducted in this area. We wanted to find out what the magnetic distribution would be in a region which abounded in various rock-types, a region whose structure was not simple but quite well known, a region hemmed in by mountains to the north, west, and south.

Before entering into the details of the survey, it will be well to briefly outline the geology of the Canon City Area. As can be seen from the accompanying geological map (Fig. 1), the area is about equally divided between sedimentary and Pre-Cambrian material. The Pre-Cambrian, consisting of granite, gneiss, and schist, is for the most part several hundred to 2,000 feet higher in elevation than the sedimentary rocks. These sediments, made up of Paleozoic, Mesozoic, and Cenozoic rocks, lie in a syncline which begins in Garden Park north of the mapped area and pitches to the southeastward. The western limb of the syncline rests at a fairly steep angle on the Pre-Cambrian, the one exception to this is in the southeast portion of the area where the sediments are involved in a steep anticline and then finally lap up against the Pre-Cambrian to the west.

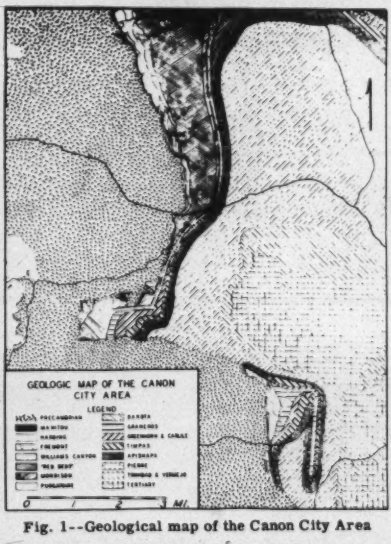

Fig. 1--Geological map of the Canon City Area

Let us now take up the details and results of the survey. The SCHMIDT vertical field-balance made by Askania was the instrument used in the investigation. The sensitivity of the balance was 27.3 gammas per small division of the scale.

For the area investigated the average number of magnetic stations per square mile was 3.4. The density-distribution of stations, however, differed greatly from place to place. Thus some areas of high magnetic relief had as many as 24 stations per square mile, while in other places of little relief the number of stations was small but adequate for our purpose. In general the number of stations was very ample in the horizons outlined by the contact between the Pre-Cambrian and the overlying sedimentaries.

Several methods were employed in fixing the geographical positions of the magnetic stations. The plane-table method accounts for the location of most of the stations. The BRUNTON compass was also used. This method was feasible because, after several weeks of plane-table work, many conspicuous points were geographically established and could be used as known points on which compass-bearings might be taken. Finally, the use of the speedometer proved very practical in places where straight roads were plentiful.

In the field six readings were made with the magnetometer at each station. Three of these readings were with the north pole of the balance in the west, and three in the east. The average of these readings was corrected for temperature and latitude. The latitude-correction was made on the basis of information supplied by the HOWE and KNAPP magnetic charts published by the United States Coast and Geodetic Survey. For the Canon City Area the latitude-correction was about 11.4 gammas per mile. Since the longitude-change per mile is small, namely, 5.1 gammas, this correction was considered unnecessary in our restricted region.

While corrections for diurnal variations would have been desirable, it was impractical in the field to provide for this correction. Since we had only one balance, observation by means of a fixed instrument at a base-station was out of the question. Frequent "checking in" at a base-station was likewise impossible for the reason that the rough terrain had to be traversed on foot. Some of the magnetic traverses required as much as five hours to make on foot. These could not have been covered if we had insisted on checking in at a base-station every two hours or oftener. As we shall see, the omission of the diurnal-variation correction is not serious in our investigation. The actual magnetic relief of the area is very great compared with the ordinary daily magnetic fluctuations. However, to make certain of the consistent performance of our instrument, at least two base-station readings were taken every day; often more were obtained.

The principal results of the magnetic survey are incorporated in a contour-map (Fig. 2) showing the intensity-distribution of the vertical component. Assigning the number 100 to the lowest valued contour, each higher contour differs from the preceding by a hundred gammas, which is the contour-interval. The total magnetic relief shown on the map is 1,500 gammas. We should not, however, conclude from the map that 1,500 gammas is the greatest relief which the Canon City Area has to offer. In restricted places, like over igneous pipes, the vertical component would change as much as 5,000 to 6,000 gammas within a few feet.

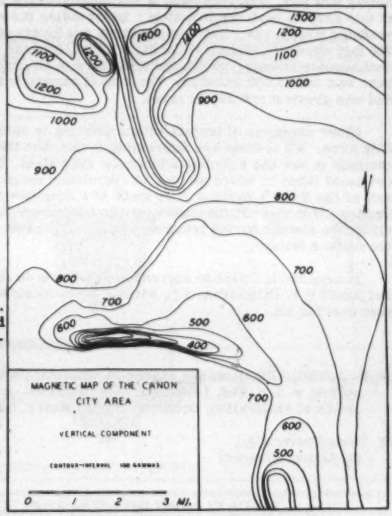

Fig. 2--Magnetic map of the Canon City Area

The first thing on the map which attracts our attention is the long narrow low in the southern portion of the mapped area. This low is along the northern base of the Wet Mountains. Field-evidence manifests a vertical fault toward the west end of the low. Talus and piedmont deposits at the base of the mountains obscure the evidence for the eastward extension of this fault. The existence of the magnetic low along the base of the mountains seems to justify us in maintaining that the fault extends eastward with the low. This fault forms the contact between the Pre-Cambrian of the Wet Mountains and the later sediments.

The second feature on the magnetic map which is of interest is the set of magnetic highs in the northwest quadrant of the map. The two western highs correlate quite well with the pegmatitic dikes which are here amply exposed. The eastern high in the group is situated in the sedimentary horizon and probably reflects the existence of these same dikes under the Paleozoic rocks.

A third feature on the map which attracts attention is the magnetic distribution in the northeastern quadrant of the map. The intensity of the field increases northward, westward, and apparently also eastward. The explanation for this anomaly is most probably the Canon City syncline. This syncline begins north of this quadrant and pitches southeastward. The intensity of the magnetic field simply indicates how near the basement-complex is to the surface; the nearer the Pre-Cambrian, the more intense is the field. In other words here we have an example of a correlation between the magnetic field and the structure of the buried crystalline rocks.

In addition to the general features of the magnetic field as indicated on the map, there are some local features which are of interest, namely, those related to terrain-effects. That terrain does influence the magnetic field is, of course, not a new concept [see 1 of "References" at end of paper], and my purpose here is to indicate some specific examples of it in the vicinity of Canon City.

Readings taken near the bottom of the canyon of the Arkansas River were on an average about 250 gammas lower than those on the plateau above. Again, along a mountain road from Canon City to Westcliffe, Colorado, three sets of readings were taken. The geology along the route is Pre-

Cambrian of the Wet Mountains, and while magnetic readings in igneous horizons may be erratic because of rapid lithologic variations, still the following does seem significant. In a deep, narrow canyon the average magnetometer reading was 22.1. In the same valley, but in a place where the distance between the canyon walls was greatly increased, the reading was 43.5, an increase of over 500 gammas. Continuing up along this road the canyon finally opened into a broad expanse of a high plateau. Here the reading was 49.1, or about 150 gammas above the second reading.

The last example of terrain-effect which I shall present refers to a series of magnetic readings taken on the southern face of a mountain northwest of Canon City. This series of observations began at the foot of the mountain and ended at the crest; the total change in elevation being nearly 900 feet. The rock-type of the mountain face is biotite granite and appears homogeneous in this respect from top to bottom. In ascending the southern steep face of this mountain four readings were taken. The second, third, and fourth stations were respectively about 300, 600, and 900 feet above the station at the base. With increase of elevation the vertical component became continuously stronger so that the difference in readings between the crest of the mountain and its base was over 3,000 gammas. The rate of change in magnetic intensity increased with elevation and was greatest toward the crest.

Other examples of terrain-effect differing in nature from those just cited exist in the Canon City Area. All of them are interesting in this that they impress on one the necessity of being cautious in how one correlates magnetic anomalies. Lithology and subsurface structure are the two usual items to which we look in correlating magnetic anomalies. In reality, however, the terrain of the Earth's surface is as much of a structure in the Earth's magnetic field as any subsurface structure. Furthermore, surface features, like hills, may cause greater magnetic anomalies than similar buried features because of greater contrast between the permeability of air and the surface feature.

In conclusion I wish to express my gratitude to the Reverends JAMES B. MACELWANE, S.J., and JOSEPH R. GOBERNA, S.J., without whose assistance in the field this survey could not have been carried out.

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RESULTS OF AN INVESTIGATION TO DETECT AN INTER-SOLAR CLOUD OF CHARGED PARTICLES DURING MAGNETIC STORMS

Robert S. Richardson

Although it is commonly assumed that terrestrial magnetic storms are caused by streams of charged particles ejected from sunspots passing across the lines of force of the Earth's magnetic field, actually no direct observational evidence for such phenomenon exists.

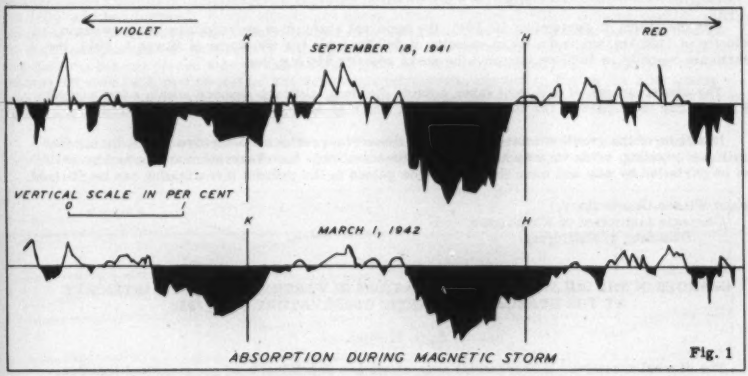
The suggestion was first made by S. CHAPMAN [Mon. Not. R. Astron. Soc., v. 89, p. 456, 1929; see also Geomagnetism, v. 2, p. 804, 1940] 15 years ago and discussed again more recently that such a stream might be detected by comparing selected regions of the solar spectrum during magnetic disturbance with the same region during magnetic calm. For if the atoms composing the stream are of the same kind and in the same state of excitation as those that produce the FRAUNHOFER lines, after ejection they should continue to absorb but on the violet side of the normal lines. This absorption will depend upon the intensity of the stream, the velocities of the particles, the geometrical relationship among the Earth, Sun, and stream at the time, and would doubtless be different for different storms.

The type of absorption anticipated is a faint continuous band or possibly several bands extending from the center of the line toward the violet to an extreme distance of 22 Å calculated by MILNE for the K-line of ionized calcium. The lines considered most likely to show absorption bands during magnetic disturbances are H and K of CaII, the most powerful lines in the observable solar spectrum.

Photographs of H and K suitable for this purpose were obtained at the Snow telescope of the Mount Wilson Observatory during two violent storms of the sunspot-cycle now near its close. The first order dispersion of the grating where the plates were taken is 1.4 Å per mm. The first set of observations was taken 20 hours after the sudden commencement of the great storm which began at $04^h\ 12^m$ on September 18, 1941. The second set of observations consists of a series taken before and after the great storm which began at $07^h\ 27^m$ on March 1, 1942, although there was a sudden commencement on February 28 at $15^h\ 48^m$. In this storm, I was fortunate in securing plates on February 25, 27, 28, and March 1, or from 56 hours before to 16 hours after commencement. Clouds prevented observations on February 26 and after March 1.

Spectrograms were taken near the center of the Sun's disk and also of the sky about one solar radius outside the limb.

These plates taken during magnetic disturbance were compared with others taken during periods of magnetic calm with the same instrument, all calibrated with the same raster and developed with the same technique. Microphotometer-tracings were reduced to intensities in the usual way.



ABSORPTION DURING MAGNETIC STORM Fig. 1

It might seem that to compare two sets of nearly identical intensities would be a simple straight-forward procedure but in practise this proved far from the case. The preliminary results indicated that if any absorption occurred during magnetic disturbance it must be very small, say less than five per cent.

To gain some idea of how much absorption could be detected by comparison of different plates, a series of exposures was made in which the appearance of an artificial absorption-band to the violet of H and K was created by interposing obstacles a few inches in front of the plate. The results showed that a weakening of the continuous spectrum amounting to about three per cent which was the smallest produced could be detected from the tracings with considerable assurance.

Originally I had hoped to be able to compare continuous intensity-curves derived from readings taken on the tracings at intervals of one mm. However, it was found impossible to make sure that identical wave-lengths were always under comparison especially when the slope was steep as with a sharp absorption-line. Hence, these curves were regretfully abandoned and the following method of reduction finally adopted.

Intensities on a uniform scale were determined for 221 well-marked points of maximum, minimum, and inflection between λ 3867 and λ 4000. This covered a region to the red of H and to the violet of K, respectively, about equal to the distance between the lines. To reduce the effect of accidental errors, smoothed values were obtained from the 221 points by taking running means of 25 at a time. The same points were always included in corresponding means or otherwise serious differences would immediately arise. Thus, if for some reason a point was missing from the

magnetic-storm intensities the corresponding point was omitted from the comparison-intensities.

From the spectral regions where absorption was theoretically impossible, corrections were determined which forced the magnetic-storm intensities to agree with the comparison-intensities on the average to within less than one-half of one per cent. The corrections thus determined were then applied to two regions extending 14 Å to the violet of H and K where absorption was anticipated. It was decided not to make a comparison over the extreme predicted range of 22 Å as the corrections when extrapolated became rather uncertain. Curves giving the differences, (Intensity magnetic storm - intensity magnetic calm), for the storms of September 18, 1941, and March 1, 1942, are shown in the Figure. These curves pertain entirely to the spectrograms taken near the center of the disk. Results for September 18, 1941, are for this single date. The curve for March 1, 1942, was formed from the mean of the intensities for February 25, 27, 28, and March 1.

With a full realization of the numerous uncertainties involved, I feel there is evidence for an absorption-band beginning near the center of H and K and extending about 12 Å to the violet with a maximum depth of slightly less than one per cent. The plates for February 25, 28, and March 1 agree in showing the band clearly but on those for February 27 it is not nearly so conspicuous. February 25, 26, and 27 were magnetically calm.

For the storm of September 18, 1941, the apparent absorption corresponds to a maximum velocity of 1100 km/sec and a mean velocity of 680 km/sec; for the storm of March 1, 1942, the maximum velocity is 1000 km/sec and the mean velocity 550 km/sec.

The spectrograms of sky-light taken outside the limb, although exposed within a few seconds of those near the center of the disk, gave curves which showed no evidence of absorption.

It will be of the greatest interest to repeat these observations a few years hence during the cycle just starting, when we may hope that the time available for observation and reduction will not be curtailed by war and when the experience gained in the present investigation can be utilized.

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CHANGES IN THE SOLAR-DIURNAL VARIATIONS IN VERTICAL MAGNETIC INTENSITY AT THE HUANCAYO MAGNETIC OBSERVATORY, 1922-1943

A. G. McNish

The diurnal variations in terrestrial magnetism are dependent upon geographical location. The variations seem more closely dependent upon geomagnetic latitude than upon geographic latitude, which leads to the belief that the configuration of the Earth's general magnetic field is a determining factor in the form of the diurnal variations.

If such is the case then there should be changes in the form of the diurnal variations at any particular station associated with secular change of the Earth's general magnetic field. At most stations secular change occurs so slowly and dependence of the diurnal variations upon the general field is so loose that no conspicuous change in the diurnal variations is observed during the course of the established programs of observation.

One of the elements whose variation is associated with the distribution of the general field is vertical intensity which exhibits a midday minimum in the Northern Hemisphere and a midday maximum in the Southern Hemisphere, in the algebraic sense, the transition from northern type to southern type occurring approximately at the magnetic equator. At an equatorial station where large secular changes in vertical intensity have occurred a reflection of these changes in the diurnal variation should be observable. Such a station is the Huancayo Magnetic Observatory of the Department of Terrestrial Magnetism, Carnegie Institution of Washington.

When the region was surveyed for the establishment of this Observatory, magnetic dip and vertical intensity were of the sign applying for the Southern Hemisphere, showing that the station was then south of the magnetic equator. During the building of the Observatory increases in vertical intensity placed the station in the Northern Hemisphere, barely across the equator, magnetically, when observations were begun in 1922. During the ensuing two sunspot-cycles vertical

intensity further increased from 324 gammas in 1922 to a maximum of 1167 gammas in 1938 after which time the value has slowly fallen off.

From 1922 to 1932 marked changes in the character of the diurnal variations at Huancayo took place as has been previously reported [see 1 under "References" at end of this paper]. During 1922 the variations exhibited midday maxima in both the southern summer and the northern summer as well as in the annual means for quiet days, which is characteristic of a station in the Southern Hemisphere (see Fig. 1). At this time Huancayo was barely north of the magnetic equator. But during 1932 the variations during northern summer were characteristic of the Northern Hemisphere while the variations during southern summer still retained their southern characteristics, the average for the year having been intermediate in character. At this time the magnetic equator had shifted well to the south of Huancayo. Both 1922 and 1932 were years of extremely low sunspot-numbers and are closely comparable for magnetic phenomena. A similar change continued during the period 1933-43, although at a less rapid rate. During the southern summer in 1943 there was no evidence of the southern type of variation.

Although the phenomenon is observable on other classes of days, quiet days were selected for most detailed examination since they are most free from effects of magnetic activity. Even on the magnetically quiet days characteristic features of the diurnal variations associated with magnetic activity may be observed. These effects are conspicuous in Figure 1 which shows a general shift in phase of the variations as the sunspot-cycles progressed. For this reason it is not allowable to make comparisons of the years of different activity. Results of observations for two complete sunspot-cycles are placed side by side in the Figure to facilitate comparison. Thus 1922 is to be compared with 1933, and so forth. The distinctive differences occurring during the intervening period are conspicuous when comparisons are made between variations for years separated by one sunspot-cycle.

A statistical examination of the reality of the change was presented in the earlier paper in which this effect was discussed. It was shown that the change in character of the diurnal variations

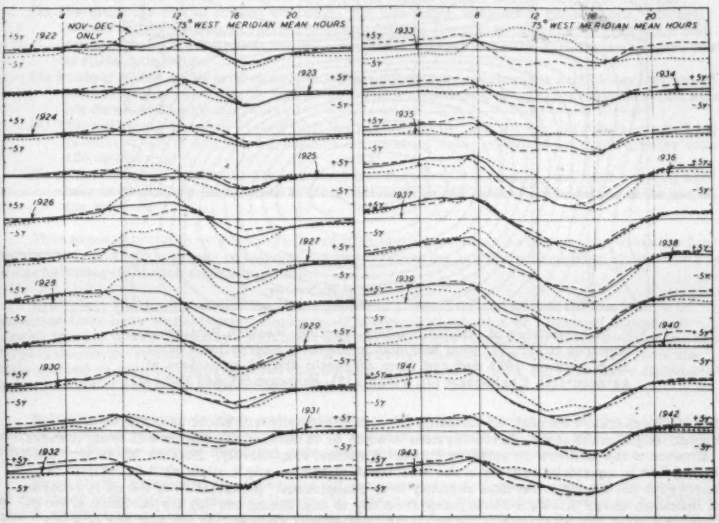

Fig. 1--Diurnal variation in vertical intensity, five international quiet days, Huancayo Magnetic Observatory, 1922-43

..... Group I, southern summer (January, February, November, and December)
– – – Group III, northern summer (May, June, July, and August)
——— Mean for year

in vertical intensity from 1922 to 1933 was much larger than could be attributed to chance. In that paper the prediction was made that during the next few years the variations at Huancayo would more strongly take on characteristics of the Northern Hemisphere. The prediction is borne out by observations obtained during the last sunspot-cycle.

How so small a secular change in vertical intensity can produce this difference in the character of the diurnal variations is revealed by examination of the diurnal variation-field in the Western Hemisphere. In general the diurnal variation-field may be thought of as due to two vortices of current centered just before the noon meridian, one north of the equator and the other south of the equator, the northern current-system flowing in a counter-clockwise direction and the southern current flowing in a clockwise direction. Owing to the separation of the geographic and magnetic equator near the 75° west meridian, a very intense flow of eastward current occurs in equatorial regions of the Western Hemisphere [2] (see Fig. 2). If an observatory is located directly under the

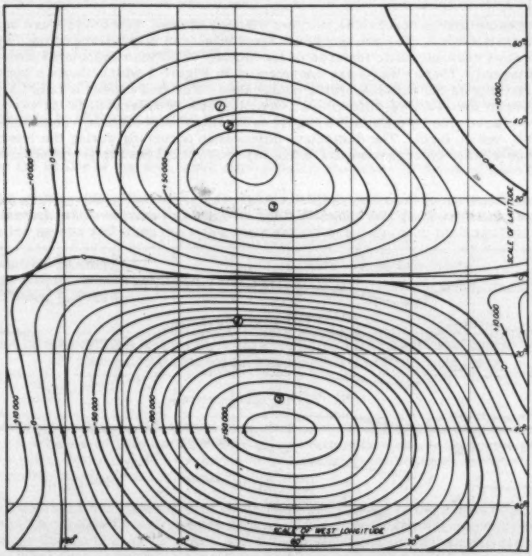

Fig. 2--Isometrics of external current-function, Western Hemisphere amperes at 11^h, 75° west meridian mean time, international quiet days, equinox 1923 deduced from magnetic diurnal-variations at Agincourt (1), Cheltenham (2), Vieques (3), Huancayo (4), and Pilar (5)

center of this eastward current, no variation in vertical intensity will occur as the system passes overhead. Slight shifts of the current-system to north or to south of the station will bring it under the influence of the southern or northern current-systems, respectively. Because of the very concentrated flow in equatorial regions in the Western Hemisphere only a slight shift in location is necessary for the effects in vertical intensity to be conspicuous. Examination of the daily records from Huancayo shows that such shifts occur from day to day, during one day the variation in vertical intensity being characteristic of the Northern Hemisphere while during the next day or a few days later it may be characteristic of the Southern Hemisphere. With the continued increase of vertical intensity at Huancayo the effects of the northern current-system become increasingly dominant as revealed in the mean variation for the seasons and for the year.

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AN EXPERIMENTAL STUDY OF THE RADON-CONTENT OF SOIL-GAS

Edward Michael Kovach

Summary--The experiment at Fordham is the first investigation of its kind in this country since 1912, when J. C. SANDERSON examined the radon-content of the soil-gas in New Haven, Connecticut. The present investigation was made in conjunction with Dr. VICTOR F. HESS'S analogous study of the penetrating-radiation of the soil.

About 75 feet from the Physics Building on lawn-covered ground, three pipes were lowered to 25, 75, and 150 cm, respectively. In the course of 69 days of actual investigation to May, 1944, covering 198 individual experiments, the radon-content of the soil-gas was measured in the three pipes simultaneously. By use of an ionization-measurement apparatus employing a Wulf double-fiber electrometer the amount of radon was calculated in curie/cc $\times 10^{-14}$. Particular use of drying and filtering tubes and an aneroid manometer was made to insure the intake of true soil-gas at various depths and to obtain an accurate measurement of the radon.

From the results obtained the following conclusions can be drawn:

(1) Freezing of the ground produces the highest values for the radon-content of soil-gas.
(2) The more the soil is soaked with water the less radon is found in the soil-gas, although, of course, the amount of radon reproduced within the soil is constant; it is obvious that occlusion and absorption of radon is greatly increased when the soil-capillaries are partly filled with water.
(3) Prolonged dry spells with almost dry ground tend to produce some sort of equilibrium of the radon-concentration in the soil-gas with a constant ratio of radon-concentration among the three depths chosen.
(4) This ratio was found as 21:38:67 for the depths 25, 75, and 150 cm; thus it seems that the radon-content of soil-gas approaches a maximum value at depths not much greater than 150 or 200 cm.
(5) Meteorological factors as air-temperature, barometric pressure, and wind-velocity are only of secondary importance in their influence on the radon-concentration of the air in the soil.

This experiment is to be continued in order to more accurately ascertain the results so far established, to study seasonal influences and to correlate the results with pending experiments on the penetrating-radiation from the ground.

Historical background--With the investigation of J. ELSTER and H. GEITEL in 1900 in the Baumann Cave near Wulfenbuettel, Germany, of the rapid dissipation of electrical charges in closed spaces, it was definitely established that the electrical conductivity of the atmosphere was largely due to the radioactivity of the soil. A negatively charged wire exposed in the air of the cave showed an activity which decayed exactly as can be expected when the first three disintegration-products of radon (RaA, B, C) were collected.

Subsequent experiments made systematically justified the statement that all the solid constituents of the Earth contain minute admixtures of radioactive substances, which when measured in an ionization-chamber produce small but quite noticeable increases in the ionization.

Since all the samples of the Earth give off emanation, the soil-gases which fill the capillaries of the Earth must contain radon and thoron. In 1902 this fact was first established by J. ELSTER and H. GEITEL [see 1 of "References" at end of paper]. Subsequent investigations were made by H. EBERT and P. EWERS in Munich in 1903 [2], H. A. BUMSTEAD and L. P. WHEELER in New Haven in 1904-05 [3], R. SCHENCK in Kiel in 1905 [4], H. BRANDES in Kiel in 1905 [5], VON DEM BORNE in the Erzgebirge in 1905 [6], A. GOCKEL in Freiburg, Switzerland, in 1908 [7], J. C.

SANDERSON in New Haven in 1912 [8], J. SATTERLY in Cambridge, England, in 1911-12 [9], J. JOLY and L. B. SMYTH in Dublin in 1911 [10], K. KAHLER in Potsdam in 1913 [11], J. R. WRIGHT and O. F. SMITH in Manila in 1915 [12], J. MUNOZ DE CASTILLO in Madrid in 1918 [13], P. J. OLUJUC in Freiburg, Switzerland, in 1918 [14], H. BENDER in Innsbruck in 1934 [15], and H. ISRAEL - KAEHLER and F. BECKER in Bad Nauheim, Germany, in 1936 [16]. Since the first World War, the experiment carried out at Fordham is the third known investigation of the radon-content of soil-gas. There has been no experiment in America since 1912.

The geological formation of the rock in Eastern Bronx, the location of Fordham, is a combination of Fordham Gneiss and Manhattan Schist. The Gneiss is a gray, narrow-banded rock composed of quartz, biotite mica, and feldspars, showing shistose appearance in many places. The Manhattan Schist, a foliated crystalline rock, consists of muscovite mica and quartz. Upon this rock-formation there is subsoil containing fragments of partly decayed rock. The uppermost layer is a residual soil, an admixture of decomposing vegetable matter.

This study was made in conjunction with the experiments carried out by Dr. HESS in 1943 and 1944 on the penetrating-radiation from the soil. It seemed desirable to find a connection between the fluctuations of the radon-content of the soil and the variations of the penetrating-radiation from the ground. Thus this experiment is a link and analagous with the comparative study of the actual variations of γ - radiation found by Dr. HESS.

Apparatus set-up at Fordham--The method employed in this study was somewhat similar to the ones used by previous investigators with improvements to avoid possible errors introduced by adverse experimental conditions.

About 75 feet west from the Physics Building a plot of lawn-covered ground was chosen as the most suitable and convenient location for the experiment. It was known from the gardener in charge of the grounds, and also from the presence of very old trees on the lawn, that the ground had not been turned up within the past 100 years. Due to the elevation of the ground on two sides of from three to four feet unnecessary flooding due to rains and to thawing was avoided.

Three holes were bored into the ground, 25, 75, and 150 cm, respectively, and corresponding lengths of one-half inch gas pipe with the bottom ends opened were lowered. Care was taken that the lower open end of the pipe was not clogged with soil. A ramrod was then inserted into the pipe and the bottom end was found clear. On the top end there was attached a removable stop-cock arrangement necessary to keep the upper end closed when not in use. A small quantity of cement was placed over the ground immediately around the pipes to secure them in place, to keep in the soil-gas, and to prevent rain-water from seeping down and clogging up the bores. Constructed around and over the three pipes was an equilateral triangular box, sides 46 by 20 cm, with a hinged cover, always locked when not in use. This arrangement safeguarded the pipes from all disturbances, from the weather and from the neighbors, that may in any way interfere with the results desired. At intervals, particularly after a heavy rainfall or thawing, each pipe was tested internally by a wad of cotton attached to the end of a brass plunging-rod for the possibility of vapor-condensation or seeping water. At all times the three pipes were found free from water-content. With all these precautions, definitely soil-gas, uninfluenced by any foreign condition which may have otherwise existed at the pipes, was inhaled into the ionization-chambers.

The radon was collected directly in the previously evacuated ionization-chambers. Three such chambers (brass cylinders 13.1 cm in diameter and 28.2 cm in height, with a volume of 3.88 liters) were used in each experiment, in connection with a Wulf bifilar-electrometer. At the top end of each chamber a brass electrode (diameter 3.2 mm and length 21.6 cm) was inserted, insulated from the outer chamber by rock-amber. Each condenser-chamber could be fixed on top of the electrometer during the time of measurement. Two stop-cocks of glass were attached on the side of each chamber, one at each end, for purposes of evacuation and filling and also for attaching an aneroid-type manometer. In an applied field of 30.8 V/cm the fiber of the electrometer and the electrode connected with it were charged negatively, while the wall of the chamber and the electrometer-case were grounded. In order to obtain a well-defined value of the saturation-current it is customary to apply the electric field in such a direction that the RaA atoms which are positively charged will be deposited at the inner electrode.

The filling and measurement--About one day before each measurement, all the chambers were carefully evacuated and refilled with "aged" (non-radioactive) dry nitrogen, after which an electric field of 30.8 V/m was established. Thus the amber adjacent to the charged inner electrode was always kept in the same state of polarization and any seeping in of charge during the time of

measurement was avoided.

Each experimental reading was usually made in the early afternoon. First, a background-reading of one scale-division was made, with the sensitivity of the electrometer known as 3.26 volts per scale-division (V/s-d). Calibration-curves were repeatedly taken with precision and only the linear part of the curve was used. The sensitivity mentioned above was evaluated from the slope of the calibration-curve.

Upon the evacuation of the chamber it was filled with soil-gas in the following manner. Connected in series between the pipe and the chamber there was set two glass filtering tubes; one was filled with cotton to absorb all foreign particles (dust and nuclei), while the other was partly filled with Phosphoric Anhydride (P_2O_5), which acted as an absorber of moisture contained in the soil-gas. The latter was necessary to avoid disturbances in the insulation of the chamber. Before the intake an aneroid-manometer was attached to the chamber and a test was made in the whole line to the ground-pipe for any leakage, thus avoiding the possibility of inhaling the atmospheric air rather than the soil-gas. This also aided in determining the speed of filling. The intake took from one to four minutes depending on the condition of the soil and the temperature of the atmosphere; the former, if very wet, necessitated a slowing down of inhalation, while the latter, if low, required a speeding up to insure the operation of the stop-cock by not allowing the grease to harden.

Two hundred and twenty volts were then applied between the electrode and the wall, and the chambers were allowed to stand from one to three hours, or both, depending on the time the reading was taken. During this time a drying tube with P_2O_5 was attached to the chambers to remove any possible moisture that might still have been present. It is necessary that the chambers be allowed to stand from two and one-half to three hours in the field in order that the radon and its decaying products (RaA, B, C) come into radioactive equilibrium with each other.

The ionization-current increases all the time during these first three hours, according to the increase of amounts of RaA to RaC. Experimentally it was found that the saturation-current taken one hour after filling the chamber was 86.6 per cent of the maximum value reached after three hours. Thus it was found possible to shorten the time for these experiments, in accepting this factor 0.866 as divisor for the one-hour reading, in order to obtain the final "three-hour" equilibrium-value. The readings were taken over five scale-divisions repeated four or five times depending on the length of each reading.

In the protocol for each day of the experiment the following measurements were listed. The temperature (°C) of the air in the shade and the temperature gradient (°C/cm) of the ground from the surface to a depth of 55 cm, for the purpose of ascertaining the extent of the frozen depth. Temperature-variations of the ground play an important part in the explanation of the fluctuation of the radon-content in the soil-gas. In obtaining the ground-temperature gradient a hole 0.6 cm in diameter was bored 55 cm deep. A standard centigrade thermometer was lowered into the bore and allowed to stand at various depths for readings. It was never necessary to go beyond 55 cm, since on all days, except one, "freezing-point depth" never went below 25 cm. The barometric pressure at the time of intake and the pressure-gradient for the previous 12 hours were taken as recorded on a barograph. The average wind-velocity for the day and the average wind-velocity for the previous 12 hours were taken from the monthly Weather Bureau report issued from New York by the United States Department of Commerce. From the same report the amount of precipitation since the previous reading was also noted. Conditions of weather and ground for each day were recorded as observed. Remarks on the possible explanation for the readings of the day and the calculations for all values found were made.

Calibration of the apparatus in "curie"--Two standard radium-solutions of 10^{-9} grams of radium from the National Bureau of Standards were used for this purpose. These solutions were poured into pyrex washing bottles with stop-cocks and ground-glass joints all lubricated with graphite flakes to avoid contact of radon with grease of any kind. The solutions were freed of emanations and then, the radon, accumulated over a known period of time, was introduced into the ionization-chamber with inactive nitrogen as carrier.

Several calibrations of this sort gave an average value of 1.61×10^8 volts/sec for one curie. This corresponds to 5.28×10^6 electrostatic units of current per curie, taking the capacitance of the Wulf electrometer plus ionization-chamber as 10.35 cm. The latter value was obtained by direct calibration of the apparatus with a Gerdien variable condenser, kindly loaned by the Department of Terrestrial Magnetism of the Carnegie Institution of Washington.

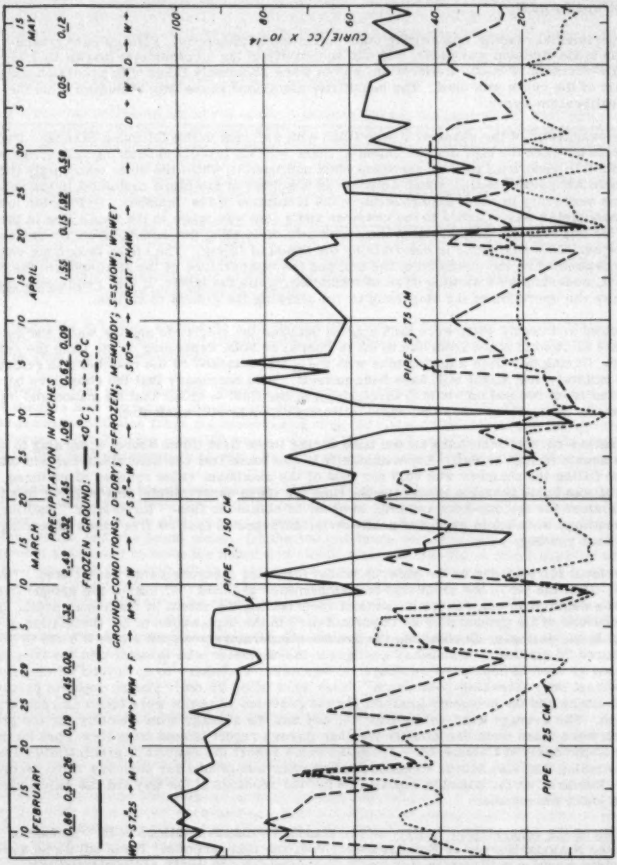
CURIE/CC X 10-14
PIPE 3, 150 CM
PIPE 2, 75 CM
PIPE 1, 25 CM
FEBRUARY
MARCH
APRIL
MAY
PRECIPITATION IN INCHES
FROZEN GROUND: —— <0°C; --- >0°C
GROUND-CONDITIONS: D=DRY; F=FROZEN; M=MUDDY; S=SNOW; W=WET
WD+ST25 → W → F → MW+FRW → F → M+F → W → FS → W
5 10 → W → GREAT THAW →
D → W → D → W →

Fig. 1--Three depth-curves of radon in soil-gas

Results obtained--From the curves obtained as plotted on Figure 1, with the experimental days as the abscissa and the radon-content in curie/cc $\times 10^{-14}$ as the ordinate, it is evident that the maximum values in all three pipes were obtained at the beginning of this series of experiments during the month of February. The subsequent months show a steady though somewhat variable decrease till the month of May when it seems the radon-content has reached an approximately stable low value. The continuation of these curves to be derived from the extension of the experiment should prove interesting, since one of the purposes is to determine the possibility of a state of equilibrium in all three pipes during a long spell of fair weather.

During the whole experiment the amount of radon-content increased with depth. The rise and fall of the curves for the three pipes occur, in general, simultaneously. There are some exceptions and these are most puzzling, since they seem to be a result of a combination of forces which are not acting at all the three depths. At times it is extremely difficult to separate and distinguish the various influences upon the radon-content particularly during the winter and thawing season, for here we have at the same time snow, frozen ground, water-content in the capillaries of the soil at above freezing-temperature, strong winds, and pressure-gradient variations. Definitely during this time the capillaries of the soil through which the radon-content escapes into the air are closed tightly by the frozen and soaked ground. This resistance in the soil voided greatly the effects of barometric pressure and wind-velocity which under normal conditions (dry soil) play an important rôle.

Interpretation of the curves--(1) A constant uniform variation in all three pipes during a particular period of days, such that the peaks and troughs run parallel, indicates the external influence of barometric pressure or wind-velocity variations, or a change in temperature is acting in all layers at the same time. Naturally one may expect diminution of the relative amplitude of the variations of radon with depth.

(2) A lagging of similar variations in the pipes indicates the influence of ground-conditions, save that the external cause in spite of ground-conditions be extended over a longer period when its influence would be noticeably felt in the deeper pipes.

(3) An opposite reaction in the lower pipes to that in the 25-cm pipe, when the latter is directly under the influence of atmospheric conditions, indicates that the reactions of the lower depths must be predominantly due to ground-conditions.

(4) The forces which influence the content of radon of the air in the soil can be listed as follows: (a) Ground-conditions, including frozen or soaked ground, and dry ground; (b) wind-velocity; (c) barometric-pressure gradient; (d) temperature-fluctuations.

Naturally, the same considerations - with certain modifications - could also be applied to the content of thoron of the air in the soil-capillaries. The measurements described here are practically unaffected by thoron since this gas (half-value period, 54 sec) decays very quickly and only prolonged exposure (one to three days) could collect considerable amounts of its long-lived decay product ThB (half-life period, 10.6 hours).

The author made an experiment which showed directly that in the soil itself the ionization produced by the products of thorium is of the same order of magnitude as the ionization produced by radon and its decay-products. A brass cylinder was lowered into a wider cylindrical cavity of the soil, about one foot deep, at - 1800 volts for three days. The activity collected showed - after the first few hours - a decay-period of about 11 hours, clearly indicating that only ThB was left at that time. Extrapolation of this curve to the time when the cylinder was taken out from the pit showed that the contribution of the products of thorium to the total ionization is about equal to the one of those of radon, as surmised by A. S. EVE in 1911. The present investigation deals only with the radon-content of soil-gas.

Frozen ground--The radium contained in the soil-material gives off radon which, as a noble or inert gas, escapes without chemical reaction into the air contained in the soil. This emanation depends for its release from the soil into the atmosphere upon the condition of the former. If the Earth's capillaries are clogged up by frozen rain or condensation, then the means of escape is lessened and the radon-content of the soil-gas is increased. Thus we find that frozen ground has the greatest influence upon the radon-content of the soil-gas. The maximum values for all pipes, therefore, appear during these subfreezing temperature-intervals in the month of February and the first few days in March. It is during this time also that we obtain three high levels or plateaus for all pipes, which values were never repeated during the subsequent months. The maximum values are:

Pipe No.	Date 1944	Content curie/cc $\times 10^{-14}$
1 (25 cm)	February 17	74.2
2 (75 cm)	11	80.9
3 (150 cm)	14	102.9

These are higher than those obtained by any previous investigator, the nearest being H. BENDER in Innsbruck in 1932 where he obtained 68×10^{-14} for 25 cm and 90×10^{-14} for 100 and 150 cm.

In obtaining the temperature-values of the different levels in the ground it was possible to establish the frozen depth when it existed. It was found that from February 9 to 16 the frozen depth varied from 5.4 to 55 cm; for March 2 and 3, 38 cm and five cm, respectively; for March 9 and 10, 16 cm and five cm, respectively; for March 20 to 23, from five to 7.5 cm; and for April 5, five cm. For the intervals up to March 23 we have from 0° to 2° from 15 to 30 cm. From March 24 to April 5 there is only surface freezing spasmodically and beyond April 6 there is no freezing at all. Thus it is to be noticed that we have maximum peaks in all pipes during the five periods during which the ground was at or below 0°C.

The following tabulation gives peak-values for all pipes in curie/cc $\times 10^{-14}$:

Pipe No. 1		Pipe No. 2		Pipe No. 3	
Date 1944	Value	Date 1944	Value	Date 1944	Value
Feb. 12	49.8×10^{-14}	Feb. 11	80.9×10^{-14}	Feb. 14	102.9×10^{-14}
Mar. 3	55.1×10^{-14}	Mar. 3	43.8×10^{-14}	Mar. 3	92.9×10^{-14}
11	25.5×10^{-14}	13	53.7×10^{-14}	11	81.3×10^{-14}
23	18.7×10^{-14}	20	54.6×10^{-14}	21	74.9×10^{-14}
Apr. 5	25.2×10^{-14}	Apr. 5	41.5×10^{-14}	Apr. 5	85.6×10^{-14}

The presence of snow on the ground enhanced the content of radon of soil-gas but was not of greater influence than the frozen ground itself. Thus we have higher values when there was no snow at all. For instance, the readings after the first period mentioned above are higher than those of the last two when we had a snow-covered ground. It is to be noticed, however, that the highest value of all on February 14 from pipe No. 3, 102.95, was obtained on a day when the snow had melted slightly and was subsequently frozen. Again, in the fifth period of April, mentioned above, we notice great values for two of the pipes, since an unusual snowfall of 10.5 inches completely covered the whole campus of the University. Here again the increase was in all pipes and could not have been due to atmospheric conditions, since during this time the pressure had dropped from 30.20 inches to 29.80 inches and the wind velocity had increased from 10 mi/hr to 33 mi/hr, all conducive to a reduction of content.

Thus it can be safely asserted that frozen ground produces the greatest values by impeding the escape of radon into the atmosphere and thus increasing its content in the soil-gas.

Soaked ground--Previous investigators have asserted that water-soaked ground increased the radon-content of the soil-gas. On the basis of results obtained in the experiment this general statement must be qualified. Water-soaked ground slows up greatly the diffusion of emanation. While the radium continues to produce radon, still it is mostly absorbed by the water-content such that the emanation does not escape into the soil-gas. While we should have expected high readings for water-soaked soil, it was found that there was a decrease in the radon-content, and noticeably so.

The winter of 1943-44, as a whole, was not severe. With the additional temperature-readings of the ground at different depths it was definitely known when the ground was not frozen but rather in a state of saturation or in the process of thawing. Thus we find great troughs particularly in the 150-cm pipe (see Fig. 1).

The readings in curie/cc $\times 10^{-14}$ show the influence of water-content upon radon. On March 7 with 1.32 inches of rain plus the water-content already in the ground we noticed a sudden drop for all pipes, up to and including March 9, as noted below:

Pipe No.	March 6	March 7	March 8	March 9
1	53.7	15.5	8.5	5.2
2	.....	50.5	13.8	5.5
3	92.7	92.4	72.4	57.4

During March 6 to 9, 1944, there was a rising barometer (29.85 inches to 30.31 inches) and a decreasing wind-velocity (dropping to maximum 25 mi/hr). The water-content is the only explanation left.

The effects of the heavy rain of March 13, 2.49 inches, are noted below:

Pipe No.	March 11	March 13	March 14	March 15	March 16
1	25.5	4.2	5.3	4.6	6.3
2	37.3	53.7	43.4	43.7	38.9
3	81.3	61.4	46.1	26.0	23.7

From March 11 to 13 there was a drop in pressure (30.68 inches to 30.20 inches) and a rise in velocity of the wind from 11 mi/hr to 35 mi/hr; this should have caused a decrease in the content of March 13. However, while it may have affected pipe No. 1, pipe No. 2 increased, and there was no effect upon pipe No. 3, which during March 13 to 16 constantly decreased. Strangely pipe No. 3 hit a lower reading than pipe No. 2. Since the content of radon-emanation increases with depth, then if the decreasing cause were solely from outside the soil from the atmosphere, Nos. 2 and 3 should have been affected somewhat proportionately. Thus, it must have been the soil-condition at 150 cm that was influencing the radon-content. At this time it was definitely known that the temperature of the ground at all depths was above the freezing-point. The prevailing influence here must have been the water-content.

After the snow had melted and the "freezing-depth" had vanished in the ground after March 23, we definitely observed the influence of water upon the radon which occurred in subsequent days. Up to March 23, 1.77 inches of precipitation was in the ground, collected during the previous week, plus the precipitation already there. We observe a drop in pipes Nos. 1 and 2 followed by a great dip in No. 3, with new lows for Nos. 1 and 2, after an additional rain of 1.06 inches on March 28 and 30.

Pipe No.	March 23	March 24	March 25	March 28	March 29	March 30
1	18.7	15.2	17.8	19.7	5.6	1.1
2	48.9	.....	17.1	30.5	21.0	15.7
3	59.6	.....	75.8	52.2	8.5	13.7

During this dropping-off period we have a constant increase in pressure (29.75 inches on March 24 to 30.6 inches on March 30). From the wind-velocity curve the highest value of 38 mi/hr was reached before the reading on March 28, which was high, and then dropped to 13 mi/hr. The ground-conditions seem to be the sole explanation.

The greatest dip in the pipes came on April 21, 1944, at a time when the effect that should have been produced by a constant high pressure of 30.25 inches from April 18 to 22 and a low wind-velocity, averaging ten to twelve mi/hr, was diametrically opposed to the results actually obtained. On April 16 and 17 there was 1.55 inches of rain. It is at this time that we have the great thawing season and it is just previous to the period in which some sort of stability is reached in all three pipes.

Pipe No.	April 19	April 20	April 21	April 22	April 24
1	22.0	25.8	1.1	7.8	9.8
2	37.8	34.3	22.1	26.1	34.4
3	63.2	65.0	5.3	16.5	28.9

Thus the low reading for pipe No. 3 at least continues on for three days. Again it is to be noted that the third pipe drops lower in value than the second. This last feature is brought out once more under the final quotation of this section. With 2.07 inches of rain on April 22 to 25 and with the barometric pressure increasing during this time, with the possibility of the wind-velocity affecting pipe No. 1 only on April 28, we observed the following results:

Pipe No.	April 26	April 28	May 1
1	24.1	1.1	19.2
2	22.2	41.7	41.8
3	61.4	31.0	55.5

It is also to be noted here that the second pipe went lower than the first, and the third lower than the second.

Other quotations could be made but these are prominent. It seems conclusive that such instability of the radon-content of soil-gas, since it is not caused by external factors, must necessarily be under the influence of ground-conditions. It is not the freezing itself but the water-content which swallows up the emanation before it reaches the soil-gas.

Dry ground--The condition of dry ground was reached apparently around the beginning of May, though we had two short rains and the ground was still moist from the heavy rains of previous months. There was no real spring and the warm weather came on rather suddenly. During this time it is noted that the curves become more stabilized and much lower in content save for the second pipe. During this stable period it is evident that the radon-content increased with depth. Whether the various depths will reach an equilibrium later on is still to be investigated.

During the dry weather the pores of the Earth are open and excessive content escapes. It is during this time that we hope to be able to observe directly the influence of atmospheric conditions upon the radon-content, such as temperature, pressure, and wind-velocity. Since not many dry-weather days are involved to May 17, not much can be said in this respect at present.

Temperature-variations--Since the variation in volume of soil-gas is $\pm 1/273$ per °C, it is obvious that an increase in temperature of the soil-gas will cause some of it to escape, and thus the remaining air will contain less radon.

This is the story of the whole curve from the high values of February to the stable low values of May. As the ground became warmer the soil-gas expanded and sought a means of escape. While this condition was always working one way or the other, still due to the continuous presence of all other factors, it is almost impossible to observe this influence directly in individual cases, but only as a "seasonal" effect. Later experiments will show this seasonal effect more clearly.

May 8 and 9 were two beautiful warm sunny days. During this time the wind-velocity decreased (20 mi/hr to 4 mi/hr) and pressure constantly increased (30.15 inches to 30.45 inches). Thus we should expect an increase in content, but actually a decrease was noted in pipe No. 1.

Pipe No.	Date	Air-temp.	Ground-temp.	curie/cc $\times 10^{-14}$
1	May 8, 1944	16°.5	16°.8	20.8
1	May 9, 1944	21°.0	18°.2	13.1

It should not be forgotten that cooling of the ground during the night produces a shrinkage of the volume of the soil-gas and, therefore, an admixture with atmospheric air which is low in radon-content. In spite of this dilution with atmospheric air the soil-gas accumulates radon during the night on account of the continuous production of radon from the soil.

Barometric pressure-gradient--The pressure-gradient, taken for the previous 12 hours, was considered sufficiently representative in determining its effect upon the soil-gas, though a continuous rise or fall over a definite period was paramount in importance. The variation in pressure causes an unbalanced relationship with the pressure of the ground. If there is a decrease, some of the soil-gas escapes into the air, resulting in a lowering of radon-content of the air in the soil. When the pressure increases, radon is retained in the soil. While this effect can be observed at times, it is difficult to distinguish it from others influencing the radon-content at the same time. Again, there are many instances when this pressure-effect is working in the same direction and at the same time with the influence of the wind.

The peaks of February 17 in all pipes when the temperature of the ground was rising occurred when we had a rise in pressure from 29.70 inches on February 15 to 30.60 inches on May 16, falling off slightly to 30.50 inches on May 17, and then dropping sharply to 29.85 inches on May 18. At peak-values the velocity of the wind was 11 mi/hr.

Pipe No.	Feb. 15	Feb. 16	Feb. 17	Feb. 18
1	41.5	51.9	74.2	41.4
2	54.4	63.1	72.2	45.6
3	83.5	94.5	97.4	93.1

Wind-velocity--By BERNOULLI'S principle the wind moving with an increased velocity over the surface of the ground causes a decrease of the pressure at that point and results in a suction-effect upon the soil-capillaries. Thus the escape of emanation is greatly facilitated by the wind. This effect under normal conditions should be felt throughout the different layers of the soil under investigation. The escape of the upper layers of the soil-gas causes a flux from the lower levels resulting in a decrease in radon-content even in deeper layers.

February 23 showed a noticeable drop in radon-content in all pipes when the velocity of the wind was 46 mi/hr, the highest reached for a 12-hour period during the whole experimental time. On February 21, the average velocity was 20 mi/hr. The results for February 21 and 23 were as follows:

Pipe No.	Feb. 21	Feb. 23
1	49.2	33.4
2	60.1	42.7
3	94.9	88.7

On March 1 there was a wind-velocity of 44 mi/hr. Here definitely we had a great dip in all pipes. Pipe No. 2 was previously measured on February 24 due to the use of the chamber for standard measurement-tests. Since there was an immediate rise after the reading of March 1, however, we can safely say that it likewise was affected.

Pipe No.	Feb. 29	March 1	March 2	March 3
1	12.3	11.0	23.9	55.1
2	.....	24.5	37.3	43.8
3	86.9	81.7	82.8	92.9

There was a quick restoration to higher values on March 3 when the wind-velocity dropped to seven mi/hr. It is probable that the rise in pressure from 29.90 inches to 30.25 inches on March 1 assisted the rapid restoration of high content.

It is hoped that these three last influences will be apparent more individually during the coming weeks of the experiment. While these are of vast importance, still it is evident that they are subservient to the conditions of the ground. This resistance offered by the soil to outside influences seems to be primary.

Conclusions--The conclusions drawn at this point of the experiment are:

(1) The greatest values are obtained when the ground is frozen.
(2) Water-soaked ground decreases proportionately the diffusion of radon into the soil-gas.
(3) Dry weather leads to stability in the three layers, establishing the fact that radon-content increases with depth.
(4) Atmospheric influences are secondary to the ground-conditions of the soil.

The continuation of the experiment will have to definitely establish these results and other effects still under investigation.

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ON THEORIES REGARDING SOME ELECTRICAL ASPECTS OF THUNDER-STORMS

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Since the present position of theories regarding the generation of electricity in storms has been reviewed in recent years by several writers [see 1 and 2 of "References" at end of paper], it is not our purpose here to present such a review. The chief purpose is rather to indicate: (a) Some conditions which must be satisfied by any theory; (b) some problems which must be solved; and (c) some specific information which must yet be obtained before one can ascertain whether any one of the proposed theories is acceptable.

Sir GEORGE C. SIMPSON in his presidential address before the Royal Meteorological Society [1], January 28, 1942, said: "In my address last year I pointed out that electricity plays little or no part in the process of condensation which is the first step in the formation of cloud and rain. Yet both clouds and rain, and still more so snow, are often highly charged with electricity. It is clear, therefore, that the electricity must be produced after the cloud, rain, and snow have been formed. That is a generally accepted fact; but I regret to say that it is about the only fact on

which there is general agreement. Today after 50 years of intensive study we do not know the precise method in which clouds and rain become electrified . . . . ."

The regret expressed here doubtless is fully appreciated by all investigators of atmospheric electricity. Although we know of several charge-generating processes which may be operative in the atmosphere, there is no theory which clearly shows how the electric charge on cloud and rain may be built up by one or more of these processes. The present improved knowledge about electrical aspects of thunder-storms prevents one from entertaining many theories which were in vogue at one time or another in the past and yet too little is known for one to make a reliable appraisal of those suggestions which have not been definitely refuted. Because of this circumstance, all that shall be attempted here is to examine a few aspects of the theories which at present seem plausible.

The electrical cycle of the thunder-storm may be regarded as consisting of the following steps: (a) An initial separation of charge, a small-scale phenomenon in which some particles of precipitation become charged with electricity of one sign and the adjacent air, or some of the smaller particles, becomes charged with the other sign. (b) A large-scale separation of charge, possibly occurring in several steps, by which large "clouds" of charge of several cubic km in volume are formed at more or less definite levels in the thunder-cloud. (c) The initiation of discharge from a cloud, namely, the mobilization of the charges, residing on particles widely distributed throughout the "charge-cloud," and thus preparing for the succeeding steps which constitute the lightning-discharge proper. (d) The lightning-discharge.

The last of these, the lightning-discharge, has been comparatively well elucidated in recent years and shall not be discussed here; several excellent general discussions of this have been published [2,4]. Knowledge regarding the other steps, however, is in an unsatisfactory state. More factual evidence is required before theories of these aspects of the electric cycle of the thunder-storm can be securely established.

Knowledge about the fundamental processes which may be involved in the development of charge in a storm is little more than qualitative. The violent disruption of water-drops is a charge-developing process which has been accorded considerable study but some of the quantitative information one requires in order to satisfactorily ascertain whether this is important in a storm-cloud has not yet been reported. Indirect evidence such as the low temperature in regions where the main charges are found, however, indicates that this process plays a minor role. That collisions between solid particles effect a separation of charge is definitely manifested by the electrical phenomena of dust-storms and of drifting snow, but the writer has found no reports on the quantitative effects which would be produced by the collision of ice-particles under conditions similar to those in the free atmosphere. It does appear, however, from the results of laboratory experiments with dusts, as well as from other indirect evidence, that this is a considerably more effective charge-separating process than any other that has been suggested. The ion-capture process proposed by C. T. R. WILSON to account for the charging of rain-drops has been verified by laboratory experiments [5] but it has not yet been proved that this would be effective when ice particles alone are involved. This process requires that a relatively large concentration of ions, preferably of low mobility, obtains in the electrically active part of a storm-cloud but such a condition has not yet been observed, except as a local phenomenon of relatively rare occurrence, namely, at times when glow- or brush-discharge (St. Elmo's fire) occurs. Unless there is some potent source of such ions other than the glow- or spark-discharge, WILSON'S ion-capture process can act only in a secondary role after fields capable of initiating glow-discharge have been developed by another mechanism.

Other processes which have been invoked in recent theories are (a) the sudden freezing of supercooled water-drops [6] and (b) either evaporation or condensation, or both [7]. W. FINDEISEN [8] is said to have found from laboratory experiments that sublimation, evaporation, and the formation of sleet (Vergraupelung) are attended by the development of electricity. Discussion of these processes should perhaps be postponed until further laboratory investigation of them is made, but from general considerations it seems unlikely that evaporation, condensation, or sublimation are active enough as charge-separating processes to play an appreciable part in developing the electrical charges of storms. For example, one would expect that the charges of one sign, possibly developed by these processes, would appear in the air in the form of ions of about molecular size and that, at the surface of the Earth, the air-conductivity and the ratio of positive to negative conductivity would both depart from normal during the formation or evaporation of dew or frost and that, even if the charged particles given off to the air were large, the potential-gradient would show a response during these occurrences. Such effects are not detected in the numerous records of these elements which have been examined by the writer.

Doubtless, further observations and experiments designed to test the validity of the several proposals are desirable. Until better evidence to the contrary is seen, however, the writer will favor the view that collision between ice-particles is the principal charge-separating process in the thunder-storm. The drifting of snow gives rise to much more prominent electric effects than does the formation of white caps at sea. Laboratory experiments with snow or ice-particles unfortunately have not been made in such a way as to yield a quantitative measure of the effectiveness of this process, but it seems likely that the charge developed per gram of agitated material is considerably greater for most dusts than for water. WHITMAN [9] found for dusts values as great as 600 esu/gm whereas the largest value found for water by P. LENARD and associates in spray from an atomizer was about 2 esu/gm. Apparently the charge developed per gram of material involved increases rapidly with increase in agitation in case of dusts or with the violence of disruption in case of water and on that account this simple comparison alone may not be decisive. But when the conditions of the experiments and other experience are considered it seems likely that the dust was agitated less violently than the water and that in both experiments conditions were more favorable for effective separation of charge than conditions that probably obtain in the atmosphere.

In order that charge be separated by the impact of ice-crystals it seems necessary that the energy expended on impact be not less than a certain minimum surface-concentration, the value of which has apparently not been determined. Thus if the relative velocity of two particles is less than a certain value, no charge can be developed. For velocities greater than this the probability that a charge be developed is doubtless an increasing function of relative velocity. In the laboratory experiments this condition doubtless was realized for a much larger proportion of the particles than in the average storm. Also, because the concentration of particles was doubtless much greater than in the atmosphere, the probability of collision between particles was doubtless correspondingly greater in the experiments. With few exceptions, such as hail, the ice-particles observed in the atmosphere are rather small and the relative velocity between particles of similar shape in a straight wind is definitely limited to a few meters per second no matter how great the wind-velocity may be, but in regions of turbulence the relative velocity of collision may be of the order of the wind-velocity. Such considerations lead one to question whether charge can be developed at an adequate rate by this process except in the more turbulent portion of thunder-storms. This uncertainty should be resolved by suitably designed laboratory experiments.

After a satisfactory mechanism has been found for the initial small-scale separation there still remains the problem of accounting for the large-scale separation, namely, the formation of "clouds of charge" in which a net charge of some tens of coulombs occupies a space of some cubic km. It is usually assumed that gravity and the drag of the vertical wind are the principal forces acting in this mechanism and that the particles with charge of one sign are larger than the oppositely charged ones. The importance of these factors can scarcely be questioned, but probably another factor--the action of the electric field upon the charged particles--has not been adequately stressed. In laboratory experiments charges of about 4000 esu/gm have apparently been developed on individual drops [10] of sprays or of agitated dust-particles [9]. For such a ratio of charge to mass the electrical force acting on the particle would exceed that of gravity for a field-strength of 10,000 volts per meter. Fields of that strength occur at the Earth's surface during storms and no doubt fields of much greater strength occur in the atmosphere near the charged clouds. Although it seems likely that the force acting upon charged particles may differ from that acting on neutral particles, this cannot be decided until information is at hand regarding (a) the ratio of charge to mass for the charged particles in clouds and (b) the field-strengths which are built up. A ratio of charge to mass as great as 4000 esu/gm would of course be unstable if the particles (assumed to be conducting spheres) have a diameter greater than about 0.1 mm, even in the absence of an external field (cloud field), and in an electric field only particles of correspondingly smaller size would be electrically stable. Much smaller ratios (of the order one esu/gm) seem to have been tacitly assumed in most theories but the observations of GSCHWEND [11] show that for rain-drops and for snowflakes at the Earth's surface this ratio not infrequently is greater than 100 esu/gm and it was doubtless much greater when these entities were first charged, unless the final charge was chiefly determined by a secondary process, such as ion-capture. It is also readily seen that drops of the maximum size that would be mechanically stable in the atmosphere could not have a ratio as great as 100 esu/gm.

The maximum strength of the cloud-field which may be built up in a storm has not been definitely determined, although the electro-altigraph records obtained at the Kew Observatory [12,13] lead to the surmise that this is considerably smaller than has been assumed heretofore. Certainly more decisive information on this point is needed, and in connection with this it would be helpful to know the charge and size of the particles in the cloud. If the charge divided by the square of the effective radius is large for a fair proportion of the particles the discharge of a cloud may be initiated for a general field that is much less than breakdown strength.

The initiation of a lightning-discharge--the getting together of the charges which are widely distributed on ice-particles or rain-drops or both--is one of a number of unexplained aspects which cannot be adequately discussed in the space of this paper, but it seems to the writer that certain forms of charge-distribution are more favorable than others for the glow-discharge, which is doubtless involved and which probably starts at the surface of charged particles, to spread throughout a sufficient volume of the charge-clouds and mobilize electricity in sufficient quantity and at adequate rate for the average lightning-discharge. Apparently the type of information regarding charge-distribution which is needed in this and some other considerations of electrical aspects of storms can be obtained only by direct exploration of the storm-cloud with suitable equipment.

The initial rate at which the charge of the average thunder-cloud is regenerated, after a discharge, is apparently of the order of four amperes [14]. In order to ascertain whether a proposed mechanism can account for this, one requires information about the distribution and size of particles, the average net charge per particle, wind-velocity and its distribution, and the size of the region in which separation of charge occurs. With the information at present available all that can be done is to estimate the order of magnitude of the limits of some of these factors. For example, (a) it is estimated that for any uniform wind the cross-sectional area of the region of separation of charge is probably not less than ten square km, unless the concentration of particles of a given size is much greater than has been reported for different forms of precipitation or the size of particle is greater than the largest stable water-drop, and (b) that the average charge per unit-mass of the particles cannot be much less than the largest values derived from GSCHWEND'S observations unless in addition to the provisos made above, the cross-sectional area of the region of activity is surprisingly large. Since some of the particles are certainly electrically neutral and since others may carry a charge of sign opposite to that which predominates in a charge-cloud, the ratio of charge to mass for some of the individual particles must be considerably larger. In making these estimates it was assumed that whatever the nature of the charged entities they may be regarded as charged spheres. Although this assumption is not strictly valid the departures from it are apparently such as to increase the estimates of the cross-sectional area of the electrically active center of a storm-cloud. In case of water-drops the departure is doubtless negligible except for drops close to the maximum stable size. Ice-particles may perhaps be regarded as though they were electrical conductors [15] but their shape is often far from spherical. Because of the latter the maximum charge that could be carried may be considerably less than was allowed in the estimates. Also when size and shape are considered it seems likely that the terminal velocity, except for hail, is usually less than that allowed. Because of these factors and in view of the nature of other assumptions, the size of the active region may be much larger than that estimated. Escape from the conclusion that the cross-sectional area of the electrically active region of the average thunder-storm is probably at least ten square km seems possible only if the concentration of particles is much greater in that region than any value the writer has seen reported or if the average velocity of particles of one sign relative to those of the opposite sign is greater than the maximum terminal velocity of water-drops. For some models of the thunder-storm ten square km may not seem too large but for others, for example, the model proposed by SIMPSON and ROBINSON [13] and which gives a good representation of observations only, a much smaller area can apparently be tolerated. Also a few reports of lightning-discharges from small clouds (size not ascertained) may indicate that some assumption in these estimates was not consistent with reality.

It seems unlikely that a greater velocity of separation than a few meters per second can be allowed in straight winds but in winds with a rotational component a much larger velocity of separation is possible. An attempt to elaborate upon this suggestion, namely, that the first step in the larger-scale separation depends upon the action of centrifugal force, would involve much uncontrolled speculation, but it may serve a purpose to indicate a few major features as follows: (a) That the initial small-scale separation by impact of particles and the first step in the large-scale separation would both occur in a region of turbulence; (b) that charges of one sign may be carried beyond one boundary and those of the other sign may pass through the opposite boundary; and (c) that further separation would then occur at an adequate rate if the wind on one side of the turbulent region differs enough from that on the other, either in respect to velocity or in respect to both direction and velocity.

In these estimates of the velocity of separation it was assumed that when two ice-particles collide both generally become charged with like sign (say, negative) while charge of the other sign is introduced into the air in the form of ions or particles which are so small that their velocity may be regarded as equal to that of the air into which they are introduced. This condition appears to be more favorable for the separation of charge than that in which oppositely charged particles are more nearly of the same size, but one may question whether this condition is realized in the atmosphere. If the small carriers are ions, each with one elementary charge, then in order to

maintain the charging current by straight winds the concentration of the ions would need to be so large and distributed over such an extensive area that their presence apparently should have been detected in some of the atmospheric-electric observations regularly made at the Earth's surface. Further investigation in the laboratory and in the atmosphere is required in order to dispose of this question.

Other electrical features of the thunder-storm, which should be accounted for by a charge-generating mechanism, are: (a) The apparent tendency for the main "clouds of charge" to be of approximately cumulous form; (b) the tendency of the "clouds" to be centered at more or less definite heights; and (c) the fact that the main cloud of positive charge is located at a greater height than that of negative charge with both at altitudes where the temperature is below the freezing-point. When the latter simple fact was definitely established, the once widely accepted theory of SIMPSON, which postulated the breaking of rain-drops as the primary charging-process, could no longer be entertained, except possibly as applying to secondary aspects. The other features of form and position of the "charge-clouds" would seem to demand that the wind-structure in the storm-cloud differ in some important respects from the simple models usually proposed for this purpose. The suggestion made by SHIPLEY [16], that the cloud of the heat thunder-storm contains a number of cells in the form of vortex rings, may be helpful here.

It is not expected that a complete quantitative theory of the generation of charge in the thunder-storm can be realized, but as those gaps in our information, which have been indicated in this discussion, and some others, become filled, we may expect that important advances toward that goal will be made.

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A NEW DEVELOPMENT OF THE THEORY AND APPLICATION OF THE POTENTIAL-DROP-RATIO METHOD OF ELECTRICAL PROSPECTING

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The methods of electrical prospecting may be divided into three general groups: (1) Potential methods; (2) electromagnetic methods; and (3) radio methods.

The potential-drop method belongs to the first group. In order to demonstrate more clearly what is new in the alternate method conceived by the writer, it will be necessary to make a brief review of the two procedures known and used with constant or expanding search-electrode separation. Several investigators have previously published studies on this method [see 1, 2, 3, 4, 5, 9 of "References" at end of paper].

Supposing an artificial electric stationary or quasi-stationary field generated between two point-electrodes at the limiting surface of a semi-infinite medium; the study of the said field can be made by the measuring of certain functions of the same, following several systems. In this

method measurements are made of the successive potential-drops between three search-electrodes which are moved on a line normal to the line of the current-electrodes. From the successive ratios, it is possible to determine two more functions, in vertical soundings and in horizontal mapping, which are the so-called apparent resistivity and the potential-gradient. The form of these three functions will depend on the nature of the semi-infinite medium, that is, on the electrical characteristics of its components and their distribution.

General equations

Without supposing any special or predetermined structure of the semi-infinite medium, the general expression of the potential-drop between any two points such as A and C, within the field formed between the point-electrodes E_1 and E_2 of Figure 1 is as given in equation (1).

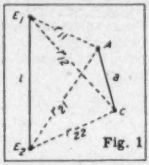

Fig. 1

$$\Delta V_{AC} = \frac{\rho_a I}{2\pi a}\left[\frac{a}{r_{11}} - \frac{a}{r_{21}} - \left(\frac{a}{r_{12}} - \frac{a}{r_{22}}\right)\right] \qquad (1)$$

Here I is the current, ρ_a is the apparent resistivity for the middle point between A and C, and a is separation between these points.

If such points are on a normal, to the line E_1E_2, we will have the conditions indicated by

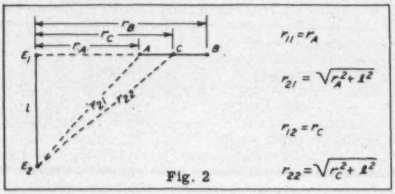

Fig. 2

Figure 2 and equation (1) will be transformed to (2).

$$\Delta V_{AC} = \frac{\rho_a I}{2\pi a}\left[\frac{a}{r_A} - \frac{a}{\sqrt{r_A^2 + \ell^2}} - \left(\frac{a}{r_C} - \frac{a}{\sqrt{r_C^2 + \ell^2}}\right)\right] \qquad (2)$$

If the electrode E_2 is very far away ($\ell = \infty$), its influence can be omitted and equation (2) will be simplified as in (3).

$$\Delta V_{AC} = [\rho_a I\,(r_C - r_A)/2\pi r_A r_C] \qquad (3)$$

Equation (3) can be written as in equation (4) if we call r the distance between the point-electrode E_1 and the mid-point between A and C and since $r_A = [r - (a/2)]$ and $r_C = [r + (a/2)]$.

$$\Delta V_{AC} = \frac{a\,\rho_a I}{2\pi\,[r^2 - (a^2/4)]} = \frac{\rho_a I}{2\pi a\,[(r/a)^2 - 1/4]} \qquad (4)$$

From equations (3) and (4) are deduced the two general expressions of equation (5) for the apparent resistivity.

$$\rho_a = \frac{2\pi\, r_A r_C}{r_C - r_A}\left(\frac{\Delta V_{AC}}{I}\right) = 2\pi a\left[\left(\frac{r}{a}\right)^2 - \frac{1}{4}\right]\frac{\Delta V_{AC}}{I} \qquad (5)$$

If there is a third point, such as (B) in Figure 2, the potential-drop between C and B, in accordance with equation (3), would be as in equation (6).

$$\Delta V_{CB} = [\rho_a I (r_B - r_C)/2\pi r_C r_B] \tag{6}$$

Dividing equation (3) by (6), we will have the general expression for the ratio of the potential-drop for the central point (C) as in equation (7).

$$(\Delta V_{AC}/\Delta V_{CB}) = r_B (r_C - r_A)/r_A (r_B - r_C) \tag{7}$$

This is usually designated by (A/B). Equation (7) will give us the so-called normal ratio, which is usually represented by F, if the semi-medium is infinite, homogeneous, and isotropic.

Equations (3) to (7), as we will see, are far from being simple; the degree of complexity will depend on the nature of the semi-medium in each special case.

Known alternates of the method

In this method penetration to greater depth is accomplished by increasing in successive stages the distance between the search-electrodes group ACB and the point-electrode E_1. The exact manner in which such increases are made distinguishes the alternate methods. In vertical soundings the electrode C remains fixed and the primary electrode E_1 is moved away from C, whereas in horizontal mapping the operation is done just to the contrary.

Alternate No. 1 (constant electrode-interval)

In this alternate the distance between A and C is the same as the distance between C and B and it remains constant during a series of observations. Let us suppose that E_1 remains fixed; the successive positions of the secondary electrodes are (see Fig. 3): A_0, C_0, and B_0; A_1, C_1, and B_1;

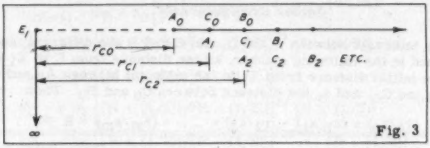

Fig. 3

A_2, C_2, and B_2; . . . . . The distances r_C are increased by a constant quantity (a), in such a way that in each position the electrodes A and C occupy respectively the C and B of the previous position, and so on. In this way an overlap of 50 per cent is obtained and the values of the ratio will be interconnected. In reality we take the inverse of such ratios. If under these conditions any initial ratio (B_0/A_0) is known, corresponding to the position $A_0C_0B_0$, and supposing an arbitrary potential-drop (A_0) between A_0 and C_0, it will then be possible to compute the corresponding potential-drop (B_0) between C_0 and B_0, which is the same as that between A_1 and C_1, and from which we will be able to calculate the corresponding potential-drop between C_1 and B_1 when the new ratio (B_1/A_1) is known, and so on successively.

In this case the normal ratio, starting from equation (7), will be expressed by equation (8) since $(r_C - r_A) = (r_B - r_C) = a$. It is convenient in this case to have r_C, the distance from E_1 to

$$F = (r_B/r_A) = [(r_C + a)/(r_C - a)] \tag{8}$$

C_1 (Fig. 3) an exact multiple of a. If we call (0) the initial position when $r_C = 2a$, then equation (8) for any other position (n) will become equation (9).

$$F = [1 + 2/(n + 1)] \tag{9}$$

This approaches unity as n approaches infinity.

The successive drops of potential permit computation of the values of the resistivity by means of equation (5). In this equation, for convenience let $(2\pi/I) = 1$. This is permissible since we assume an arbitrary initial potential-drop. This leads to a solution giving relative values of resistivity, ρ, and not the absolute values. When $(2\pi/I) = 1$, and for the conditions postulated in establishing equation (9), equation (5) becomes equation (10).

$$\rho_a = a\,(n + 2)\,(n + 1)\,\Delta V \tag{10}$$

As we will see later, equation (10), although giving continuous values of ρ, is difficult to interpret; this is one of the disadvantages of this method. Another disadvantage is that as the distance to the electrode E_1 increases, sensitivity is lost since we know that the potential approaches zero as the distance increases indefinitely.

Alternate No. 2 (expanding electrode-interval)

As in alternate No. 1, the distance between the electrodes A and C is made equal to the distance between C and B, but this distance increases as the distance r_C to the electrode E_1 increases, in order to maintain a fixed ratio $M = (r_C/a)$. In this case the increases of r_C can be constant or not. This procedure has the advantage that sensitivity remains essentially constant in any position, but has the important disadvantage that the potential-drop ratios are not interrelated. For this reason it is not possible to obtain a continuous curve for the apparent resistivity as in alternate No. 1, and only the potential-drop-ratio curves are available for interpretation. Of course, in each case these curves have a definite form.

In this alternate for a series of observations, the normal ratio will be constant under the conditions postulated. The general form starting from equation (8) is as in equation (11).

$$F = [(r_C/a) + 1]/[(r_C/a) - 1] = (M + 1)/(M - 1) \tag{11}$$

As M approaches infinity, then F approaches unity.

Author's new alternate

In this alternate the intervals between A and C, and C and B are different, and both of these separations are increased in the manner, as the distance from C to E_1 is increased. In Figure 4 let r_0 equal the initial distance from E_1 to the midpoint between A_0 and C_0. Let a_0 equal the distance between A_0 and C_0, and a_1 the distance between C_0 and B_0. Then

$$(r_0/a_0) = (r_1/a_1) = (r_2/a_2) = \ldots\ldots = (r_m/a_m) = R$$

This method permits the computation of a continuous curve of apparent resistivity under conditions of constant sensitivity. In the interpretation of this curve, the difficulties encountered in alternate No. 1 are eliminated and, in addition, a potential-drop-ratio curve is available. This alternate is especially advantageous for application to vertical soundings.

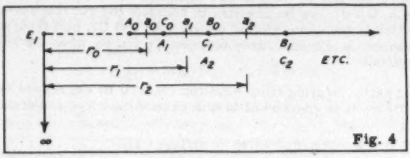

Fig. 4

The various electrode-spacings are interrelated as follows.

$$r_0 = a_0 R$$

$$r_{A_0} = [r_0 - (a_0/2)] = a_0\,[R - (1/2)]$$

$$r_{C_0} = r_{A_1} = [r_0 + (a_0/2)] = a_0\,[R + (1/2)]$$

$$a_1 = (r_1/R) = [r_{A_1} + (a_1/2)]/R = \left\{a_0\,[R + (1/2)] + (a_1/2)\right\}/R$$

Solving

$$a_1 = a_0 [R + (1/2)]/[R - (1/2)]$$

and

$$r_1 = a_1 R = a_0 [R + (1/2)]/[R - (1/2)]\, R$$

$$r_{B_0} = r_{C_1} = r_{A_2} = [r_1 + (a_1/2)] = a_0 [R + (1/2)]/[R - (1/2)]\, R + (a_0/2)\, [R + (1/2)]/[R - (1/2)]$$

$$= a_0 \left\{ [R + (1/2)]/[R - (1/2)] \right\} [R + (1/2)]$$

$$a_2 = (r_2/R) = (r_{B_0} + a_2/2)/R = \left\{ a_0 [R + (1/2)]/[R - (1/2)]\, [R + (1/2)] + (a_2/2) \right\}/R$$

Solving

$$a_2 = a_0 \left\{ [R + (1/2)]/[R - (1/2)] \right\}^2$$

and

$$r_2 = a_2 R = a_0 \left\{ [R + (1/2)]/[R - (1/2)] \right\}^2 R$$

$$r_{B_1} = r_{C_2} = r_{A_3} = [r_2 + (a_2/2)] = a_0 \left\{ [R + (1/2)]/[R - (1/2)] \right\}^2 R +$$

$$(a_0/2) \left\{ [R + (1/2)]/[R - (1/2)] \right\}^2 = \left\{ [R + (1/2)]/[R - (1/2)] \right\}^2 [R + (1/2)]$$

Continuing in the same way the general expressions in equations (12) to (17) for any position (m) are derived.

$$a_m = a_A = a_0 \left\{ [R + (1/2)]/[R - (1/2)] \right\}^m \tag{12}$$

$$a_{(m+1)} = a_B = a_0 \left\{ [R + (1/2)]/[R - (1/2)] \right\}^{(m+1)} \tag{13}$$

$$r_{A_m} = a_0 \left\{ [R + (1/2)]/[R - (1/2)] \right\}^m [R - (1/2)] \tag{14}$$

$$r_m = a_0 R \left\{ [R + (1/2)]/[R - (1/2)] \right\}^m \tag{15}$$

$$r_{C_m} = a_0 \left\{ [R + (1/2)]/[R - (1/2)] \right\}^m [R + (1/2)] \tag{16}$$

$$r_{B_m} = a_0 \left\{ [R + (1/2)]/[R - (1/2)] \right\}^{(m+1)} [R + (1/2)] \tag{17}$$

The normal ratio is constant when the value of R is fixed and combining equation (7) with equations (12), (13), (14), and (17) we get equation (18).

$$F = r_B (r_C - r_A)/r_A (r_B - r_C) = [r_B a_A / r_A a_B] = [R + (1/2)]/[R - (1/2)] \tag{18}$$

The apparent resistivity is as in equation (19).

$$\rho_a = 2\pi a_A [R^2 - (1/4)]\, (\Delta V_{AC}/I) \tag{19}$$

Or if the current is chosen such that $(2\pi/I) = 1$, then we get equation (20).

$$\rho_a = a_A [R^2 - (1/4)]\, \Delta V_{AC} \tag{20}$$

The two-horizontal-layers problem

Up to this point we have only seen the general form of the equations of the potential-drop ratio and those of the apparent resistivity; in order to show the advantages of the author's method over the two alternates previously known, we will apply the three methods to the two-layer problem.

In this case the semi-infinite medium is formed of two layers (see Fig. 5)--the upper is of a finite thickness h and the lower of infinite thickness; both layers are considered homogeneous, isotropically defined electrically by their resistivities ρ_1 and ρ_2. Above the limiting surface XX' of the postulated semi-infinite medium, there is assumed a medium of infinite resistivity ρ_0. The depth h is the unknown factor.

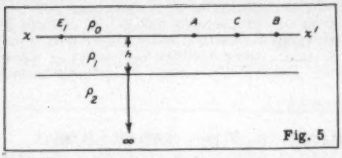

Fig. 5

The two-layer problem is very important in electrical prospecting in certain investigations of bedded structures and because it can be extended to the case of multiple layers.

If I is the current which emerges from the point-electrode E_1 and K is the reflection-coefficient at the boundary of the lower layer, which has for its value $K = (\rho_2 - \rho_1)/(\rho_2 + \rho_1)$, then applying the theory of the electrical images of MAXWELL, and taking into account that ρ_0 is infinite, and hence the medium above the surface XX' is a perfect insulator, the potential-differences between A, C, and B at the surface XX' will have values as in equations (21) and (22).

$$A = \Delta V_{AC} = \frac{\rho_1 I}{2\pi}\left[\frac{r_C - r_A}{r_C r_A} + 2\sum_{n=1}^{\infty} K^n \left(\frac{1}{\sqrt{r_A^2 + (2nh)^2}} - \frac{1}{\sqrt{r_C^2 + (2nh)^2}}\right)\right] \tag{21}$$

$$B = \Delta V_{CB} = \frac{\rho_1 I}{2\pi}\left[\frac{r_B - r_C}{r_C r_B} + 2\sum_{n=1}^{\infty} K^n \left(\frac{1}{\sqrt{r_C^2 + (2nh)^2}} - \frac{1}{\sqrt{r_B^2 + (2nh)^2}}\right)\right] \tag{22}$$

In equations (21) and (22), n is the infinite number of images of I.

From equations (21) and (22) it is easy to deduce directly the general expression for any potential-drop ratios for any separations between A, C, and B.

$$\frac{A}{B} = \frac{\Delta V_{AC}}{\Delta V_{CB}} = \frac{\dfrac{(r_C - r_A)h}{r_A r_C} + \sum_{n=1}^{\infty} K^n \left[\dfrac{1}{\sqrt{(r_A/2h)^2 + n^2}} - \dfrac{1}{\sqrt{(r_C/2h)^2 + n^2}}\right]}{\dfrac{(r_B - r_C)h}{r_C r_B} + \sum_{n=1}^{\infty} K^n \left[\dfrac{1}{\sqrt{(r_C/2h)^2 + n^2}} - \dfrac{1}{\sqrt{(r_B/2h)^2 + n^2}}\right]} \tag{23}$$

If $\rho_1 = \rho_2$ and K = 0, this equation is reduced to equation (7).

In applying the three alternates of the method we will start from equation (23).

First alternate

We know that in this case $(r_C - r_A) = (r_B - r_C) = a$; that is, the distances between the secondary electrodes are equal and constant. We can express equation (23) as in equation (24), placing the distances r_A and r_B as functions of r_C, that is, $r_A = (r_C - a)$ and $r_B = (r_C + a)$.

$$\frac{A}{B} = \frac{\Delta V_{AC}}{\Delta V_{CB}} = \frac{\dfrac{1}{[(r_C/a) - 1]\,(r_C/h)} + \sum_{n=1}^{\infty} K^n \left[\dfrac{1}{\sqrt{[(r_C - a)2h]^2 + n^2}} - \dfrac{1}{\sqrt{(1/4)(r_C/h)^2 + n^2}}\right]}{\dfrac{1}{[(r_C/a) + 1]\,(r_C/h)} + \sum_{n=1}^{\infty} K^n \left[\dfrac{1}{\sqrt{(1/4)(r_C/h)^2 + n^2}} - \dfrac{1}{\sqrt{[(r_C + a)/2h]^2 + n^2}}\right]} \tag{24}$$

In this equation appear the ratios (r_C/h), (r_C/a), and (a/h); the first two are variable for each position because r_C is also variable. Since a and h are constant, the ratio (a/h) will be constant in a given series of measurements; hence if we put the ratio $(r_C/h) = x$ and the ratio $(a/h) = c$, we have $(r_C/a) = (x/c)$, so equation (24) can be expressed as function of x and c as in equation (25).

$$\frac{A}{B} = \frac{\frac{C}{(x - C)x} + \sum_{n=1}^{\infty} K^n \left[\frac{1}{\sqrt{[(x - C)/2]^2 + n^2}} - \frac{1}{\sqrt{(x^2/4) + n^2}}\right]}{\frac{C}{(x + C)x} + \sum_{n=1}^{\infty} K^n \left[\frac{1}{\sqrt{(x^2/4) + n^2}} - \frac{1}{\sqrt{[(x + C)/2]^2 + n^2}}\right]} \qquad (25)$$

From equation (25) may be constructed curves for the computation of h once the value of c is fixed and varying x, which is the relative penetration, and giving several values to the coefficient K which, for all possible values of ρ_1 and ρ_2, varies from +1 to -1. Concerning the number of images n, it is usually sufficient to take not more than ten since the series generally converges rapidly. The normal ratio F is divided by the observed ratios (A/B) to give (FB/A).

Previously the author demonstrated [see 6] that in the two-layer problem the apparent resistivity has the general expression given in equation (26), referring to the middle distance r between A and C.

$$\frac{\rho_a}{\rho_1} = 1 + 2\left[\left(\frac{r}{a}\right)^2 - \frac{1}{4}\right] \sum_{n=1}^{\infty} K^n \left[\frac{1}{\sqrt{[(r/a) - (1/2)]^2 + (2n\,h/a)^2}} - \frac{1}{\sqrt{[(r/a) + (1/2)]^2 + (2n\,h/a)^2}}\right] \qquad (26)$$

Since, in the alternate which we are considering, the distance r varies while a is constant, the ratio (r/a) will be variable, and the ratio (h/a), for a determinated case, will be constant; but as in any investigation this ratio is unknown, since h is also unknown, the consequence is that for the interpretation-calculations such ratio is also variable. This difficulty is eliminated in the author's alternate, as will be demonstrated later.

Second alternate

In this case the equal distances between the electrodes ABC, denoted by a, are variable, and are increased in the same proportion as the distance r_C. In this case the ratios $(r_C/h) = x$ and $(a/h) = c$ are variable. Dividing, we get $(r_C/a) = (x/c)$, which is denoted by M, and is usually made between 3 and 5. Then equation (24) can be transformed to equation (27).

$$\frac{A}{B} = \frac{\frac{1}{x(M - 1)} + \sum_{n=1}^{\infty} K^n \left[\frac{1}{\sqrt{[(M - 1)/M]^2\,(x^2/4) + n^2}} - \frac{1}{\sqrt{(x^2/4) + n^2}}\right]}{\frac{1}{x(M + 1)} + \sum_{n=1}^{\infty} K^n \left[\frac{1}{\sqrt{(x^2/4) + n^2}} - \frac{1}{\sqrt{[(M + 1)/M]^2\,(x^2/4) + n^2}}\right]} \qquad (27)$$

Interpretation-graphs can be computed from this equation.

As already stated, in this case the ratio (A/B) is discontinuous and it is not possible to obtain a continuous variation of the apparent resistivity.

Author's new alternate

To establish the general expression of the potential-drop ratios we will start, as in the previous cases, with equation (23), leaving the new expression as a function of the ratio (r_C/h) and in which we shall place the distances r_A and r_B as functions of r_C, taking into consideration the equations (14), (16), and (17). It is easy to see that between such quantities there exist simple ratios which may be written $r_A = r_C\,[R - (1/2)]/[R + (1/2)] = (r_C/F)$ and $r_B = r_C[R + (1/2)]/[R - (1/2)] = Fr_C$. F is the normal ratio [equation (18)]. Therefore, the general equation becomes equation (28).

$$\frac{A}{B} = \frac{\frac{h}{r_C}(F - 1) + \sum_{n=1}^{\infty} K^n \left[\frac{1}{\sqrt{(r_C/2Fh)^2 + n^2}} - \frac{1}{\sqrt{(r_C/2h)^2 + n^2}}\right]}{\frac{h}{r_C}\left(\frac{F - 1}{F}\right) + \sum_{n=1}^{\infty} K^n \left[\frac{1}{\sqrt{(r_C/2h)^2 + n^2}} - \frac{1}{\sqrt{(Fr_C/2h)^2 + n^2}}\right]} \qquad (28)$$

Finally if we call x the relative depth-ratio (r_C/h) we can write the previous equation as in equation (29).

$$\frac{A}{B} = \frac{\frac{F-1}{x} + \sum_{n=1}^{\infty} K^n \left[\frac{1}{\sqrt{(x/2F)^2 + n^2}} - \frac{1}{\sqrt{(x/2)^2 + n^2}}\right]}{\frac{F-1}{xF} + \sum_{n=1}^{\infty} K^n \left[\frac{1}{\sqrt{(x/2)^2 + n^2}} - \frac{1}{\sqrt{(Fx/2)^2 + n^2}}\right]} \qquad (29)$$

This equation has the same general form as those previously derived and it depends only upon the relative penetration, once the normal ratio F is fixed. F in turn depends upon the ratio (r/a) = R, to which is generally given a value between 3 and 5.

The advantage of this method is principally the easy interpretation of the apparent resistivity-curves and their correlation with the values of the ratios (BF/A). This follows since in equation (26) we can eliminate one of the ratios, in this case (h/a). The latter is made a function of the ratio R = (r/a), fixed beforehand in such a way that the equation becomes only a function of the relative penetration-ratio (r/h) as in equation (30).

$$R = (r/a),\ (h/a) = R\,(h/r)$$

$$\frac{\rho_2}{\rho_1} = 1 + 2\,(R^2 - \tfrac{1}{4}) \sum_{n=1}^{\infty} K^n \left[\frac{1}{\sqrt{[R - (1/2)]^2 + (2nR\,h/r)^2}} - \frac{1}{\sqrt{[R + (1/2)]^2 + (2nR\,h/r)^2}}\right] \qquad (30)$$

With equation (30) it is possible to construct interpretation-graphs once the value of R is fixed.

To illustrate the curves of the potential-drop ratio, in equation (29) let the value of R = 5, from which F = (5.5/4.5) = 1.2222. Multiply equation (29) by F and substitute F = 1.222 in the right-hand side. Then

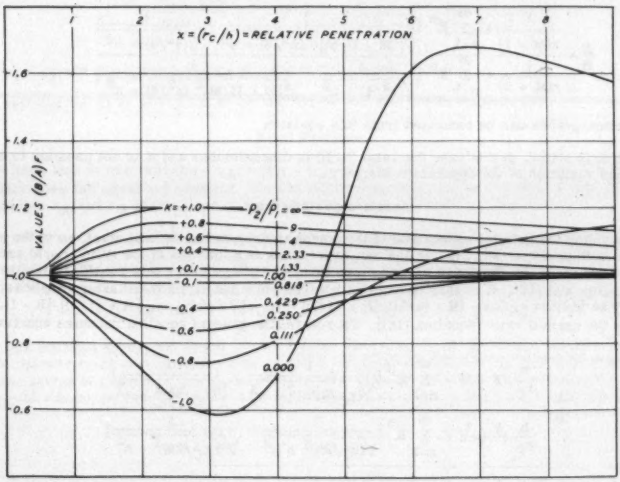

Fig. 6--Variation of the relations of potential-drop in the author's equation (31) when R=(r_C/a)=5, F=(R+0.5)/(R-0.5)=1.222....

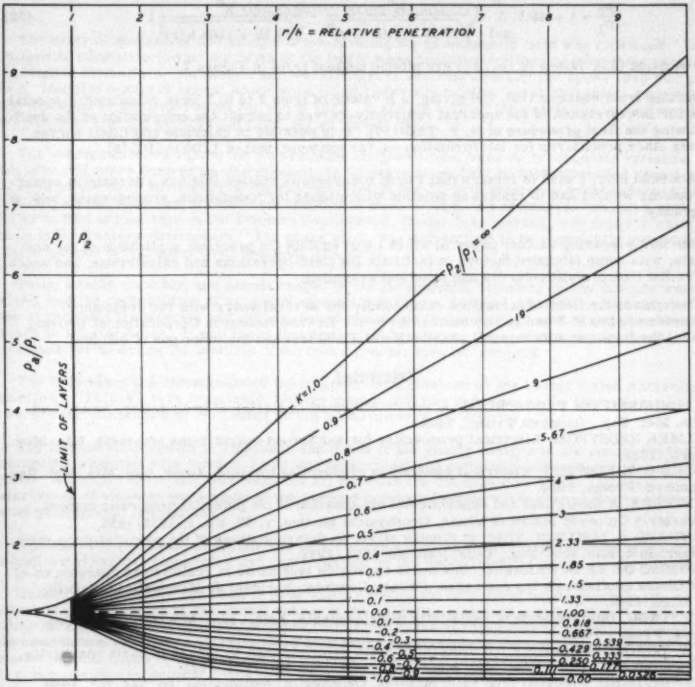

Fig. 7 -- Graphs of (ρ_a/ρ_1) versus relative penetration (r/h), when in the author's equation (32)

$$(\rho_a/\rho_1) = 1 + 49.5 \sum_{n=1}^{\infty} \left\{ K^n \left[20.25 + (10\,n\,h/r)^2\right]^{-1/2} - \left[30.25 + (10\,n\,h/r)^2\right]^{-1/2} \right\},$$

where $K > 0$ if $\rho_2 > \rho_1$ and $K < 0$ if $\rho_2 < \rho_1$

$$\frac{B}{A} F = 1.2222 \frac{(0.181818/x) + \sum_{n=1}^{\infty} \left[\frac{K^n}{\sqrt{0.25\,x^2 + n^2}} - \frac{K^n}{\sqrt{0.373\,x^2 + n^2}} \right]}{(0.222222/x) + \sum_{n=1}^{\infty} \left[\frac{K^n}{\sqrt{0.167\,x^2 + n^2}} - \frac{K^n}{\sqrt{0.25\,x^2 + n^2}} \right]} \qquad (31)$$

From equation (31), (B/A)F and x are plotted as a series of curves for various values of the parameter K between +1 and -1 as shown in Figure 6. From Figure 6 it can be seen that (B/A)F reaches a maximum when the relative penetration (r/h) = x has a value between 2.5 and 3.2. The position of this maximum determines the depth h in the field-applications.

For this same value of R, namely, 5, equation (30) becomes equation (32).

$$\frac{\rho_a}{\rho_1} = 1 + 49.5 \sum_{n=1}^{\infty} \left[\frac{K^n}{\sqrt{20.25 + (10n\ h/r)^2}} - \frac{K^n}{\sqrt{30.25 + (10n\ h/r)^2}} \right] \qquad (32)$$

From equation (32), values of (ρ_a/ρ_1) are plotted against (r/h) in Figure 7.

Starting from equation (30), and giving to R values of from 3 to 5, I have calculated a special curves for interpretation of the apparent resistivity-curves to permit the computation of the depth h, following the first procedure of G. F. TAGG [7]. It is possible to calculate additional curves following other procedures for interpretation as, for example, that of LONGACRE [8].

As a final note, I wish to remark that I have successfully applied this new alternate in numerous problems which I had to resolve in relation with studies for foundations, ground-water, and of stratigraphy.

I am now preparing another paper in which I will explain the practical application of the new alternate, with some tabulated factors to facilitate the field-operations and calculations, and which will give the interpretation-curves and practical examples.

I have made the field-observations successfully for several years with two resistance-gradiometers (types R-3 and R-1), constructed by the Heiland Research Corporation of Denver, Colorado, the first one with nominal penetration of 2,000 feet and the other one of 300 feet.

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RESEARCHES IN TERRESTRIAL MAGNETISM AND ELECTRICITY AT DEPARTMENT OF TERRESTRIAL MAGNETISM, CARNEGIE INSTITUTION OF WASHINGTON, DURING APRIL, 1943, TO MAY, 1944

J. A. Fleming

The retarding effect of the war on the execution of the normal program of the Department has again made itself felt during the year. Communications between countries have become more and more difficult and scientific research has been progressively orientated to meet the requirements of modern war. Many established organizations and observatories have found it possible to maintain a part, if not the whole, of their normal activities and accordingly the loss of continuity of accumulating data on land has not been total. Naval operations, on the other hand, have precluded the collecting of observations at sea, thus preventing the maintenance of isomagnetic charts upon which navigation and some phases of the activities of war depend. The investigation of special war-problems, however, has resulted in the development of many items of scientific value.

Geomagnetic investigations

The study of methods of analyzing and interpreting the geomagnetic field was continued. Data on magnetic anomalies in various parts of the world were compiled for determining their relation to geological formations. An isodynamic world-chart of vertical intensity for epoch 1940 was prepared. Isoporic charts of recent epoch were found regionally to show great changes in form from those prepared by the Department for epoch 1922. A simple method for prediction and extrapolation of certain types of geophysical time-series was evolved.

The average monthly values for all available stations of the solar daily magnetic variation on quiet days, S_q, were derived for the mean of the 12 years from 1922 to 1933. Detailed examination was made of the daily variability of the current-system for S_q with reference to the effect of this variability on the reduction of field-observations to mean of day. An anomalous condition in S_q similar to that at Huancayo in the Western Hemisphere, though less marked, was found to exist at Manila in the Eastern Hemisphere. The phase of S_q was determined to be practically independent of the amplitude of S_q, apart from seasonal influences.

Daily, weekly, monthly, and annual ranges in the geomagnetic elements in any latitude were derived, and the probabilities of ranges of various magnitudes deduced. An extensive study was made of recorded frequencies and magnitudes of geomagnetic fluctuations with durations of ten seconds to several hours. It was found that equipment heretofore generally used at observatories is adequate for detecting fluctuations of durations greater than ten seconds.

The reductions and discussions of the magnetic data obtained by the United States Antarctic Expedition of 1939-41 were completed, and the manuscript was prepared at the Department and forwarded for publication to the United States Department of the Interior.

The latitude-distribution in amplitude and phase of the yearly changes in the annual means of geomagnetic elements with sunspot-cycle was determined and estimated for each year from 1905 to 1940. A similar derivation was made for all latitudes for the annual variation and post-perturbation. Estimates were made of the induced currents flowing in the oceans due to short-period geomagnetic fluctuations.

A group of professional associate workers compiled data on the frequencies of geomagnetic fluctuations of various amplitudes and durations and on the reduction of geomagnetic data to epoch.

During the year there has been in progress a compilation of a list of world geomagnetic observatories accompanied by the annual values of the magnetic elements at these observatories extending back over varying numbers of years, according to the accessibility of the relevant data. This compilation represents a preliminary step in the preparation of the list sponsored in 1936 by the International Union of Geodesy and Geophysics. It is hoped that the observatories concerned will communicate corrections of any erroneous values in order that they may be incorporated in the definitive edition to be published by the Union.

General comparison and discussion were made of the following geomagnetic and solar phenomena: (1) American magnetic character-figure, C_A; (2) relative sunspot-number, R; (3) area, S, of sunspots in the central zone; (4) area, F, of flocculi in the central zone; (5) average total area, P, of prominences referred to central meridian of date; (6) average intensity, C, of the green coronal line referred to the central meridian; and (7) transmission-disturbance figures, TD. The solar data are not homogeneous because of differences in observing conditions; the resulting graphs are similar at many times but differ conspicuously in detail. Many instances of nearly simultaneous features are evident. There are, however, as many more cases where magnetic disturbances had no obvious solar cause, and cases where solar activity had no magnetic counterpart.

Radio blackouts in polar regions are found to occur during magnetic bays--typical magnetic disturbances of short duration which are preceded and followed by generally undisturbed magnetic conditions. These bays are very pronounced near the auroral zone although their magnetic effects extend to equatorial regions. During every one of 69 significant magnetic bays recorded at College, Alaska, high ionospheric absorption producing partial to complete radio blackouts was observed. The frequency of bays averaged eight a month and they usually occurred between 10^h and 18^h GMT--night at College. They frequently ran in series of two to five days, having a recurrence-interval of close to 24 hours. The similarity of these blackouts to the well-known daylight fade-outs is marked. Both effects appear to be caused by absorption due to intense ionization of the lower ionosphere. The polar blackouts, so prevalent during all magnetic disturbances, must result from particle bombardment (or equivalent) from the Sun.

One type of visual recorder incorporating a sparking device to plot changes in the Earth's field was devised. A long platinum-tipped pointer attached to the magnet-system of the variometer moves over a metallic plate as the suspended magnet deflects in the Earth's field. At intervals of about one minute a spark from the tip of the pointer to the metallic plate makes a record on a sheet continuously moving through the spark-gap. Thus a succession of points burned in the paper makes immediately apparent variation of the Earth's field with time.

In a second method a photoelectric cell is made to follow the light-beam reflected from a mirror rigidly fastened to the suspended magnet of a variometer. A pen attached to, or synchronized with, the photocell gives a record in ink of the deflections of the variometer. Any unbalance of light falling on a twin photocell results in a movement of the photocell to a new position seeking a balance. When equal amounts of light fall on both sections of the photocell, the moving pen stops until a change in magnetic field again causes an unbalance. This instrument has attractive remote-recording possibilities. The soundness of principle was demonstrated by an experimental model and further development is contemplated.

Another type of visual recorder was designed using special photographic paper which leaves a trace, immediately visible through a red filter, of deflections of the light-beam from a standard variometer.

Variometers were designed for measuring short-period geomagnetic fluctuations. Of major interest was the successful construction of the element for measuring vertical intensity, along lines formerly less successfully followed by WATSON. New detecting elements for horizontal intensity and declination permit the accurate measurement of geomagnetic fluctuations for periods as short as one-half second. Sudden changes in field such as might give rise to micropulsations not recorded by variometers with slower response can be detected and measured with these instruments. A new variometer of universal pattern for horizontal intensity, vertical intensity, and declination, involving quartz-fiber detecting elements and quartz supports was designed and constructed at the Department. A new type of portable magnetograph, embodying novel features developed at the Department, is already being constructed for use in the field as well as at observatories. Such a magnetograph is greatly needed for securing continuous reliable records over short periods (one or two weeks) for control and reduction of field-observations for which records as obtained from widely spaced observatories have proved insufficient.

Magnetic activity and properties of the ionosphere parallel roughly the 11-year solar-activity cycle. The last minimum in that cycle occurred in 1933 and another is due in 1944. It is of considerable practical value to the field of communications to foretell the minimum and hence the time when an increase in solar and geomagnetic activity may be expected. Progress of the activity-cycle was compared with the magnetic index u (smoothed), and with average maximum critical frequency of the F_2-layer (09^h, 75° west meridian time) at Huancayo. The parallelism of critical frequency, which is proportional to the square root of electron-density, with sunspot-number was much closer than that of either factor with the magnetic-index curve, and suggests the preferability of ionospheric measurements as direct indicators of terrestrial effects of sunspot-activity.

Geoelectric investigations

An investigation of the columnar resistance of the atmosphere was made. Changes in columnar resistance are attributed chiefly to changes of either the concentration or the vertical distribution, or both, of the nuclei of condensation in the lower atmosphere, on the assumption heretofore made of arbitrary forms of distribution. In one phase of this investigation, forms of distribution were sought consistent with the observed data and conforming to the meteorological or other circumstances probably prevailing at the time and place of observation.

In connection with the further reduction of the Watheroo results bearing upon the change of potential-gradient with season at that Observatory, it is to be noted that earlier results bearing on the diurnal variation of the conductivity of the atmosphere appear to be confirmed. During a succession of calm nights in winter, the diurnal variation of the conductivity of the lower layer of air (nearest the ground) varies in a manner quite independent of that of the vertical column of air regarded as a whole. When the wind remains high, the variation near the ground tends to partake of that of the vertical column as a whole. High wind at night does not appear to alter, in any appreciable manner, the variation of the vertical column as a whole, but tends to make that near the ground vary in phase with that of the whole. One of the interesting problems in atmospheric electricity, awaiting solution, is to explain why the conductivity of the vertical column varies as a whole.

Various attempts have been made to derive on a theoretical basis a relationship between the mobility and recombination-coefficient of ions. One of the latest attempts is that by HARPER [Phil. Mag., v. 29, pp. 434-448, 1940]. The ratio of recombination-coefficient to the mobility is not, according to this derivation, a constant but increases as the radius of the ion decreases. HARPER believes that the derived relationship should hold, not only for small ions, but for large ions and ions of intermediate mobilities as well. It appears to be extremely important to obtain data with which to test this relationship. MÄCHLER, in 1936, obtained data which he claims favor a formula derived by LANGEVIN (constant ratio of recombination-coefficient and mobility). However, observations of both recombination-coefficient and mobility were not made, and the values were not extended over wide ranges of mobility. HARPER points out that the theory of LANGEVIN is incomplete in that it fails to take into account the effect of diffusion in bringing the ions together. No account was taken of the effect of the size of the ion in obtaining the recombination-coefficient; hence the large ions will have, according to LANGEVIN, the same recombination-coefficient as the small ions, which is obviously incorrect. HARPER has removed these difficulties but it still remains necessary to check his theory experimentally. Data have been obtained, by means of the ion-counters, bearing on this point. Simultaneous measurements have been made upon the mobility and the recombination-coefficient of ions placed inside a closed room. Some data had already been obtained so that altogether some five points are available, the mobilities extending from that of the small ions (1.5 cm/sec/volt/cm) to the other extreme, that of the ordinary large ions (3×10^{-4} cm/sec/volt/cm). The corresponding values of the recombination-coefficients are: 1.6×10^{-6} and 3×10^{-9}. The other values of the mobilities and corresponding values of the recombination-coefficients lie between the two extremes given above. A plot of $\log_e A\alpha$ and $\log_e$ BK, results in a straight line. A and B are constants having values 10^9 and 10^4 respectively, while α is the recombination-coefficient and K is the mobility of the ions in cm/sec/volt/cm. The equation of the curve connecting the two variables is $\log_e A\alpha = (D + S \log_e BK)$. The value of S (slope of the line) is 0.73, while $\log_e D$ has a value of 0.28. The final relationship between the recombination-coefficient α and the mobility K is $\alpha = 1.1 \times 10^{-6} K^{0.13}$. By means of a theoretical formula by J. J. THOMSON connecting the mobility of the large ions with the radius of the ion, it is possible to compute the radius of the ion corresponding to each mobility and consequently to compute, from HARPER'S formula, the recombination α for each mobility-group. It is possible, by this means, therefore, to compare the computed values of (α_c) with the observed values (α_o) of the recombination-coefficient. The comparisons are remarkably close considering the number of assumptions made. For example, the values at the lowest mobility are $\alpha_c = 1.7 \times 10^{-9}$ and $\alpha_o = 3.1 \times 10^{-9}$; at the highest mobility, they are $\alpha_c = 5.4 \times 10^{-6}$ and $\alpha_o = 1.6 \times 10^{-6}$.

The observed rate of ionization of the atmosphere at the site of the Department, obtained by use of a thin-walled ionization-chamber, often reached a maximum in the early morning, then diminished to a minimum in the evening. During periods of high wind at night or during the day, this type of diurnal variation did not develop. This observation tends to confirm the theory previously suggested, that the usual diurnal variation of this element depends on the concentration of radioactive matter in the atmosphere near the ground. This concentration is greatest in early morning following a calm night. As the wind-velocity increases during the forenoon, the radioactive matter is scattered and mixed with higher layers of air, and its concentration in the lower layers of air is thus reduced until a condition of calm is approached in the evening. When the wind remains high throughout the night, and also during the daylight hours, the concentration of radioactive matter does not vary and the normal diurnal variation in ionization does not develop.

The observed decrease of the electrical conductivity of the air in a room occupied by people has been attributed to particles, or nuclei, introduced into the room with exhaled air. Some investigators, using the Aitken nuclei-counter, have not detected such particles in samples from the breath, because those particles are too large to be counted with the types of counter used. The average diameter of the particles, estimated from an experimentally determined value of their mobility, is about two microns, or 30 times that of condensation-nuclei or LANGEVIN ions. The mobility derived from the results of specially designed experiments is 3×10^{-6} cm^2 volt^{-1} sec^{-1}.

Observatory- and field-work

The complete magnetic, auroral, and ionospheric observatory established in collaboration with the University of Alaska at College, Alaska, in July, 1941, was maintained in full operation. Special studies relating to ionospheric problems were made by the Observatory's staff and charts showing graphically the systematic diurnal and seasonal changes occurring in the transmission-characteristics of the ionosphere were prepared.

The extensive geophysical programs at Huancayo and Watheroo Magnetic Observatories were continued and all resulting data were promptly communicated and made available for emergency use.

Because of commercial requirements it was necessary to end, early in 1943, the long series of earth-current records obtained at the Tucson Magnetic Observatory--a series made possible by cooperation with the American Telephone and Telegraph Company and the United States Coast and Geodetic Survey. Cooperation with the Survey in the atmospheric-electric program was continued.

Maintenance of International Magnetic Standards at the Cheltenham Magnetic Observatory of the United States Coast and Geodetic Survey was effected through the Division of Geomagnetism and Seismology of the Survey.

While no field-work other than at the observatories could be undertaken, it was possible to assist various Governments through loans of magnetic instruments to undertake new magnetic surveys and to obtain repeat-observations at established observatories.

Publications

The activities of the Department are set forth in greater detail in Year Book No. 42 of the Carnegie Institution of Washington.

The publication of the quarto volumes entitled "Scientific results of Cruise VII of the Carnegie during 1928-1929 under command of Captain J. P. Ault" has been continued. Biology IV, consisting of a number of individual reports, was issued on July 15, 1943. Chemistry I and Oceanography I-A are ready for publication, and other volumes of the series are in preparation.

A few of the principal papers published during the last year are listed below:

S. CHAPMAN, Edmond Halley and geomagnetism, Terr. Mag., v. 48, pp. 131-144, 1943.
S. CHAPMAN, Archaeologica geomagnetica I and II, Terr. Mag., v. 48, pp. 1-2, 77-78, 1943.
S. CHAPMAN, A theoretical note on the magnetic field of a circular sunspot, Terr. Mag., v. 49, pp. 37-42, 1944.
J. A. FLEMING, The Sun and the Earth's magnetic field, Smithsonian Inst., Report for 1942, pp. 173-208 with 19 pls., 1943.
J. A. FLEMING and W. E. SCOTT, List of geomagnetic observatories and thesaurus of values, Terr. Mag., v. 48, pp. 97-108, 171-182, 237-242, 1943; v. 49, pp. 47-52, 1944.
O. H. GISH, Evaluation and interpretation of the columnar resistance of the atmosphere, Abstract, Amer. Geophys. Union, Trans. of 1943, I, pp. 218-219, 1943.
H. D. HARRADON, Some early contributions to the history of geomagnetism , II, III, IV, V, and VI, Terr. Mag., v. 48, pp. 79-91, 127-130, 197-199, 200-202, 1943.
V. F. HESS, On the radon-content of the atmosphere and the radium-content of river-water, Terr. Mag., v. 48, pp. 203-206, 1943.
A. H. SHAPLEY, An estimate of the trend of solar activity, 1944-50, Terr. Mag., v. 49, pp. 43-45, 1944.
K. L. SHERMAN, The electrode-effect in the atmosphere, Amer. Geophys. Union, Trans. of 1943, I, pp. 221-222, 1943.
E. H. VESTINE, Preliminary summary of auroral observations, Meanook, Canada, December 1, 1932, to June 30, 1933, Terr. Mag., v. 49, pp. 25-36, 1944.
E. H. VESTINE, Remarkable auroral forms, Meanook Observatory, Polar Year, 1932-33, Terr. Mag., v. 48, pp. 233-236, 1943.
G. R. WAIT, Cause for the radical change with season in the type of potential-gradient diurnal-variation curves at Watheroo, Abstract, Amer. Geophys. Union, Trans. of 1943, I, pp. 219-220, 1943.

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MAGNETIC WORK OF THE UNITED STATES COAST AND GEODETIC SURVEY FROM APRIL, 1943, THROUGH MARCH, 1944

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The demands of the military services continued to occupy all of the facilities of the Section of Geomagnetism of the United States Coast and Geodetic Survey, the obtaining and furnishing of magnetic information for charts being foremost. There was an increase in the requests for the establishment of compass-roses on airfields with which to test and adjust airplane compasses.

The close cooperation maintained in former years with the Department of Terrestrial Magnetism of the Carnegie Institution of Washington was continued. That Institution loaned the Bureau field- and observatory-instruments, and the Bureau gave to it the data obtained.

Magnetic surveys

In other American Republics--The cooperative program of magnetic repeat-observations in the other American Republics, which was begun in November, 1941, continues. The second season's work, which began in October, 1942, and ended in September, 1943, included stations in Venezuela, Colombia, Ecuador, Peru, Bolivia, Chile, Argentina, Uruguay, Paraguay, and Brazil, extending as far south as Punta Arenas, Chile, on the Straits of Magellan. In Brazil the project included stations in the Amazon Valley as far west as Benjamin Constant near the Peruvian Border, and Porto Velho near the Bolivian Border. The observers compared their instruments with those at the Observatories at Huancayo (Peru), Pilar (Argentina), and Vassouras (Brazil). Diurnal observations for declination and horizontal intensity were made in the vicinity of the magnetic equator in Brazil, Ecuador, and Chile.

The third season's work began in February, 1944, when one observer went to South America to fill gaps left in the earlier program and another went to Central America.

In May, June, and July, 1943, special observations were made in the vicinity of the new Paricutin Volcano in Mexico. These included complete observations at four base-stations, and observations of vertical intensity with an Askania field-balance at over 200 stations.

In the United States--The repeat-observations required for the compilations of the 1945 isomagnetic charts of the United States were started in 1943. Because of the necessity of conserving gasoline and tires, these observations were confined to the eastern half of the country, largely to the northeastern quarter.

Early in 1944, repeat-observations were made in the Gulf States, and preparations were made for a survey of the western half of the country.

As usual, a considerable number of magnetic observations were made by parties of the Survey which were not engaged primarily in magnetic work. These included observations along the Alaska Military Highway, on both sides of the Boundary between Alaska and Canada, observations in other parts of Alaska and along the coasts of the United States, and observations by six parties making surveys of airports throughout the United States.

Table 1 summarizes the magnetic observations made during the year.

Work in the office

As in the previous year, magnetic data were furnished to nearly every mapping-service in the Government. The three-hour-range indices, K, were furnished daily to the Department of Terrestrial Magnetism of the Carnegie Institution of Washington, and to several Governmental agencies.

A program was begun for printing isogonic charts covering the entire Earth on a scale of 1:5,000,000. The compilation of the material was made necessary in furnishing the above magnetic data. The series is to include 43 charts, of which 13 were issued by the end of the year covered by this report. In compiling these charts, use is made of all available data on distribution and secular change, as well as of all available published charts. In addition to furnishing the best available magnetic information, they are on a scale which makes them quite suitable for a study of the general geography of parts of the world which were formerly little known but are now often mentioned in the headlines.

Table 1--Magnetic Stations occupied April 1943 to March 1944

State or region	Repeat-stations				Other stations	Totals
	Old		New			
	D only	Complete	D only	Complete		
Alabama	...	1	...	...	2	3
Arkansas	...	1	...	...	1	2
California	...	...	...	...	3	3
Florida	...	4	...	...	2	6
Georgia	...	4	...	...	2	6
Idaho	...	...	...	...	2	2
Illinois	...	2	...	...	...	2
Indiana	...	1	...	...	...	1
Iowa	...	1	...	...	...	1
Kansas	...	1	...	...	2	3
Louisiana	...	2	...	...	...	2
Maine	...	7	...	2	4	13
Massachusetts	...	3	...	1	4	8
Michigan	...	3	...	...	1	4
Minnesota	...	...	...	...	1	1
Mississippi	...	...	1	...	...	1
Missouri	...	3	...	...	3	6
Montana	...	...	...	...	1	1
Nevada	...	...	...	...	4	4
New Hampshire	...	2	...	...	...	2
New Jersey	...	...	...	...	1	1
New Mexico	...	...	...	...	4	4
New York	...	7	...	4	3	14
North Carolina	...	5	...	2	2	9
North Dakota	...	...	...	...	1	1
Ohio	...	2	...	...	1	3
Oklahoma	...	1	...	...	...	1
Oregon	...	...	...	...	1	1
Pennsylvania	...	4	...	4	4	12
Rhode Island	...	2	...	...	...	2
South Carolina	...	...	...	...	1	1
South Dakota	...	...	...	...	1	1
Tennessee	...	3	...	...	3	6
Texas	...	6	...	3	3	12
Utah	...	...	...	...	4	4
Vermont	...	3	...	...	...	3
Virginia	...	4	...	3	3	10
Washington	...	...	...	...	4	4
Wisconsin	...	1	...	...	2	3
Wyoming	...	...	...	...	2	2
Alaska	...	...	...	...	25	25
Canada	...	...	...	...	5	5
Mexico	...	1	...	3	...	4
Costa Rica	...	2	...	...	...	2
Nicaragua	...	1	...	1	...	2
Panama	...	2	...	...	...	2
Argentina	...	1	...	...	...	1
Brazil	...	11	...	15	...	26
Paraguay	...	...	...	1	...	1
Uruguay	...	1	...	...	...	1
Totals	0	92	1	39	102	234

The manuscript of "Magnetism of the Earth" was nearly completed. Also nearly completed were two special reports covering the work done in the other American Republics through 1943. Annual means from observatory-records were furnished to the Journal of Terrestrial Magnetism and Atmospheric Electricity for use in the Thesaurus of observatory-values.

The preparation of four volumes of results for observatories was completed during the year, for reproduction by offset lithography. These volumes are Magnetic Observatory Results at San Juan 1926-28, Cheltenham 1933-34, Sitka 1935-36, and Honolulu 1935-36.

As a result of the expansion of the work of the Section of Geomagnetism of the United States Coast and Geodetic Survey, it was necessary to move the Section to larger quarters, in the same building. The New York Computing Office continued to have a small unit processing magnetic records.

Instrumental program

The following listed new instruments, all manufactured in the United States, have been secured during the year: One new magnetometer-inductor complete, DTM CIW type; three new control-units for induction-magnetometers; partially complete detector-element for induction-magnetometer for determination of horizontal and vertical intensity.

Numerous small changes have been made in some of our field-instruments to simplify operation and to increase the accuracy of results.

An observatory-magnetometer has been equipped with a special Alnico-II magnet and has been tested over a period of more than one year. The results have been excellent and indicate that certain changes in magnetometer-design may be desirable.

Many special tests and operations have been carried out for various defense agencies.

Observatories

The five magnetic Observatories of the Survey have continued in operation without serious interruption.

Cheltenham, Maryland--The routine operation of three magnetographs has been continued. All field-instruments of the Survey and many instruments belonging to other agencies have been standardized at this Observatory. The National Bureau of Standards continues to cooperate in the matter of standardization of potentiometers, standard resistances, and standard cells, and the Department of Terrestrial Magnetism of the Carnegie Institution of Washington continues to coopera in the maintenance of International Magnetic Standards at this Observatory.

Honolulu, Territory of Hawaii--There have been some interruptions in the routine operation of this Observatory due to nearby disturbances of a mechanical nature which have been unavoidable.

Tucson, Arizona--In addition to the routine operation of the magnetic-observatory instruments, the cooperative work with the Department of Terrestrial Magnetism of the Carnegie Institution of Washington on atmospheric potential-gradient and positive and negative air-conductivity has been continued.

Sitka, Alaska--Two magnetographs have been in continuous operation throughout the year. One of the magnetographs is of the insensitive type, so designed as to record the most severe magnetic storms.

San Juan, Puerto Rico--The performance of the variometers continues to be much more satisfactory since they have been installed in a sealed housing.

U. S. Coast and Geodetic Survey,
Washington 25, D. C.

AURORAL PHOTOGRAMMETRY

E. H. Bramhall

Introduction--Continuous auroral research has been carried on in Norway by Dr. CARL STÖRMER and his collaborators during the past 40 years. By means of a network of observing stations an extensive series of simultaneous auroral photographs has been obtained there [see 1, 2 of "References" at end of paper]. When a pair of these photographs is superposed in such a way that the star-fields coincide, parallax of corresponding auroral points or of well-defined boundaries may be measured; hence distances from the observing stations may be computed. Altitudes and azimuths determined for the stars, together with these computed distances, suffice to fix the geographical position and height above the Earth for the specified points. Star-charts, or "nets", have been devised to facilitate the labor of routine computations, and these have been employed in Canada [3], Alaska [4], and New Zealand [5], as well as in Norway. However, in addition to the preparation of original charts, a considerable amount of graphical or mathematical analysis is required for the adequate reduction of the photographs to obtain position and direction of the aurora in space.

It seems worthwhile at this time to inquire into the adaptability of photogrammetric methods--now being used particularly for topographical mapping by aerial surveys--to future auroral work. In convenience and directness the technique in its present state of development appears to possess decided advantages for this application. The versatility of the technique may be judged by the fact that it has been used with equal success in mapping continents and fleas--with contour intervals ranging down to a small fraction of a mm. Its use for precise determination of the aurora in space--making feasible the ready construction of a detailed model in three dimensions--may likely provide, new, or heretofore unavailable, information on paths of corpuscles responsible for the visible aurora, as they enter the Earth's atmosphere. It is not unreasonable to suppose, further, that detailed studies of intensity-distribution with altitude may be possible, providing valuable information on the structure of the E- and F-regions of the ionosphere.

Stereoscopic perception--For photogrammetric measurements, the unaided eyes, with their interlocking nerve system, constitute a precision optical instrument of remarkable delicacy and discrimination. The merits of this instrument may best be adjudged through a simple analysis of the phenomenon of stereoscopic vision from a physical, rather than a physiological, standpoint.

Two dissimilar perspective images of an object are ordinarily formed on the retinas of the eyes. Viewed singly, these have no characteristics to indicate the third dimension, other than the relatively shorter images of equally long but more distant lines. Under the conditions of normal binocular vision, these images merge to form a single spatial model. The lines of light for the two eyes then converge on the object upon which the vision is concentrated; that is, referring to Figure 1, they cross at a distance D from the eyes. The inter-pupilary distance, B, is about 66 mm for most individuals. Then, if the distance for distinct vision is 26 cm, the angle of convergence of the eyes is: $\phi = 2 \tan^{-1} (33/260) \simeq 15°$. The range in D for distinct vision is, then, from approximately 15 cm to infinity and the corresponding range in ϕ is from 25° to 0°.

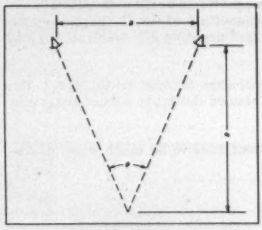


Fig. 1--Conditions for binocular vision; (B)=interpupilary distance; (D)=distance to object; (ϕ)=parallactic angle

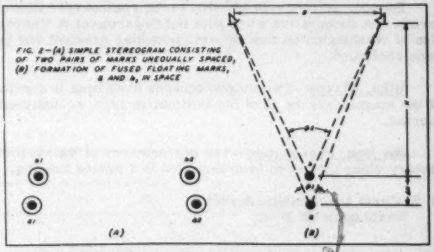


Fig. 2--(A) Simple stereogram consisting of two pairs of marks unequally spaced; (B) formation of fused floating marks, a and b, in space

In Figure 2-A a simple stereogram is shown consisting of two pairs of dots (a1 and a2, and b1 and b2) spaced at unequal distances apart, the greater being somewhat less than the inter-pupilary distance. When a1 and b1 are viewed with the left and a2 and b2 with the right eye, the observer may fuse the pairs into two floating marks, a and b, of Figure 2-B. In the fusion of these dots, b appears closer to the observer than a, since $\phi_2 > \phi_1$, and the conditions for observation of depth or distance have been realized.

As a measure of relative heights or distances of objects, either the difference between the angles of convergence--or parallactic angles ϕ_1 and ϕ_2, or the differences between pairs of image-points--or parallax of these points may be taken. In Figure 2, H represents the apparent distance apart of points a and b corresponding to a difference, $\Delta\phi$, between the angles of convergence. The maximum value of ΔH is limited by the depth of field of the eyes, this depending upon absolute distance of the objects. That is, if H is too small, and the eyes are concentrated on one object, the other object may appear as two blurred images due to lack of sufficient accommodation in the eyes to cover the depth. The minimum value of ΔH at which separate images are obtained depends upon sharpness of vision, which may correspond to $\Delta\phi$ as low as 8" for some individuals and normally to not more than 20".

For the unaided eyes the accuracy of stereoscopic perception at various distances may readily be calculated for $\Delta\phi = 20''$. If H = 26 cm, B = 66 mm, and $\phi = 20''$, the limit of stereoscopic perception is as in equation (1).

$$\Delta H = (B/2)\,[\cot(\phi_2/2) - \cot(\phi_1/2)] = 0.01 \text{ mm} \qquad (1)$$

That is, persons with normal eyesight should, with concentration, be able to perceive differences in distances of 0.01 mm at the normal distance of distinct vision without magnification.

In the examination of distant objects, when $\phi < 20''$, stereoscopic perception disappears. This limiting distance is given approximately by: $H_L = (B/\phi) \cong 680$ meters (ϕ being expressed in radians). Beyond this distance, then, the detection of difference in distance by means of parallax or by convergence of the eyes is impossible. The limit of stereoscopic perception for the unaided eyes may be expressed as in equation (2) since $\Delta\phi = (\phi_2 - \phi_1) \cong (B/H) - [B/(H + \Delta H)]$.

$$\Delta H = (H^2\,\Delta\phi/B)\,[1 + (\Delta H/H)] \qquad (2)$$

If $H >> \Delta H$, the term in brackets is essentially equal to unity. For B = 66 mm and a limiting value of $\Delta\phi = 20''$, $\Delta H \cong (H^2/680)$. ΔH may be decreased either by an increase in the stereo-base (by a factor, r) or by a magnification of the image (m). Then $\Delta H \cong (H^2/680\ mr)$.

Topographical mapping--In aerial topographical mapping, principles governing binocular visio are directly applicable. The stereo-base, B, and the mean height of flight, H, above terrain, represent the inter-pupilary distance and object-distance, respectively. Aerial cameras at Stations I and II in Figure 3 replace the eyes. Multiplex projectors, utilizing diapositives on glass, printed from the original films to the desired scale, are accurately directed to reproduce the camera-orientation in space. Their distance apart is adjusted to represent on a convenient scale the base-line between Stations I and II. The projected superposed images then constitute a stereoscopic scale-model of the terrain. The model is viewed on a movable platten in the center of which is an illuminated hole, this acting as a floating mark. Immediately under the mark a pencil point, attached to the platten, plots directly the orthographic projection of any movement of the mark in space. The vertical position of the floating mark is adjustable and may be made to coincide in space to a point on the model with an accuracy of better than 0.1 mm. The corresponding uncertainty is about three feet in a model having a scale of 1:10,000. Movement of the mark around the model, in such a way that it always appears to be in contact with it, automatically draws a contour-line for a level, which depends upon the vertical scale of the model.

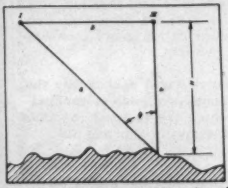


Fig. 3--Camera stations I and II, stereo-base, B, conjugate-image rays, a and b, for topographical mapping

The contour-interval required for a specific map determines the flying height, H, and the distance between exposures, B. The base-height ratio, (B/H), controls the acuteness of the angle, ϕ, formed by the conjugate image-rays, a and b, and hence, to a great extent, fixes the accuracy of mapping.

In order to take full advantage of the accuracy now attainable in aerial photogrammetry, the cameras and projectors used must be precision instruments. In addition, the technique of handling and processing the films and diapositives must be refined if distortion in the final stereoscopic model is to be avoided.

The quality of lens-systems utilized in the optical instruments largely determines that of the product. To meet the rigid specifications of the aerial photographer the following lens-characteristics are required: (1) Large field--up to 90°; (2) sharp definition throughout the field; (3) minimum distortion; (4) minimum aberration; (5) freedom from physical defects. The perfect lens has not yet been made. All suffer from the following principal defects, to a greater or lesser extent:

(1) Loss of light by absorption and reflection (this may be 30 to 50 per cent for complex lenses).
(2) Chromatic aberration for which complete correction is not possible for all colors. Correction for any two colors is accomplished by combining opposing lenses of different glasses, having different indices of refraction and dispersion. The opposing lenses are selected to correct for the two primary colors that have the greatest effect on the emulsion.
(3) Spherical aberration for which precise correction for certain parts of the field may be realized by a combination of lenses but, even in lenses of the best quality, images on flat surfaces are more sharply defined in some regions than in others.
(4) Curvature of field produced by elemental lenses, the direction of the curvature depending upon whether the lens is concave or convex. By suitably arranging opposite elements in a complex lens, such curvature may be eradicated. However, a compromise with the correction for astigmatism must be effected.
(5) Astigmatism renders the lens incapable of producing a sharp image by light passing obliquely to marginal parts of the field even in the absence of spherical aberration. It prevents the sharp definition of lines in two directions at the same focal distances. It may be largely eliminated over a considerable area in the image-plane by spacing the lenses to form an anastigmat combination.
(6) Distortion may be described as unequal magnification in different parts of the field, and its correction is of the utmost importance in photogrammetry. It may be greatly reduced by proper balancing of opposing elements in front and rear cells. To some extent, distortion produced by the aerial camera may be remedied by a projector-lens producing distortion in the opposite sense.
(7) Non-uniform illumination, that is, variation of the light-intensity passing through the lens from the center to the margin of the field, is an inherent defect which is most marked in wide-angle lenses. The illumination at the margin of the field may be 15 per cent of that at the center.
(8) Flare is the effect caused by light reflected from the lens-mount, or at surfaces of the lenses, and produces luminous spots on the photograph. It is mostly eliminated in the design of high-quality lenses.

The success of aerial topographical surveys, utilizing photogrammetric methods, affords testimony on the extent to which the above imperfections and inherent lens-defects have been overcome. Illustrative sample aerial photographs taken from an altitude of 20,000 feet with a six-inch lens, oriented 60° from the vertical, are shown in Figures 4 and 5. With such photographs on a scale of 1:20,000, if ground-control is good, elevations are obtained with errors not greater than 1/1000 of the height of the air-stations above terrain.

As in the case of most physical measurements, absolute accuracy is dependent both upon refinements of the measuring devices and technique of the observer. Errors ascribed to tilt of camera, measurement of the stereo-base, and altimeter-readings usually total not more than one per cent. If overlapping vertical photographs are used in an area where the relief is not greater than 500 feet, absolute errors in elevation may be reduced to less than five feet.

Applications of method to auroral photogrammetry--There seems no physical reason why the identical equipment and technique of aerial mapping cannot be used with equal success in auroral photogrammetry. This application imposes demands on the equipment which are in some respects less severe, and in others more severe, than required in mapping. On the credit side are the following factors:

(1) Since the camera-stations are fixed in position, the stereo-base line may be readily determined with any required precision.
(2) Differences in heights of the camera-stations do not depend upon altimeter-readings and may be accurately determined.

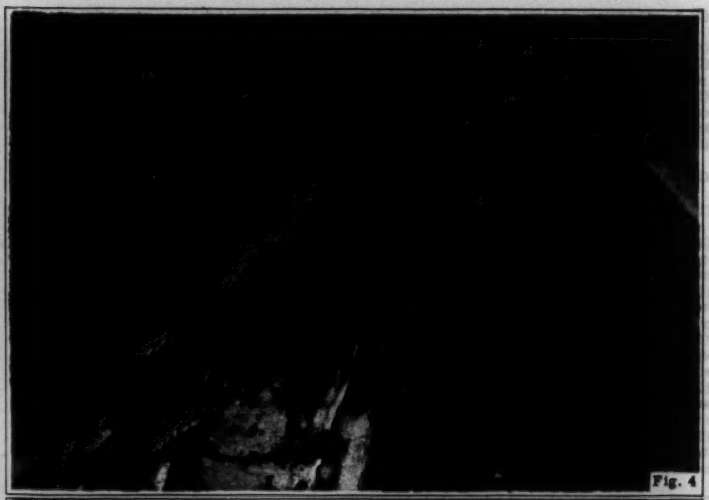


Fig. 4

Fig. 5

Figs. 4 and 5--Oblique views of geological formations from 20,000 feet with aerial mapping-camera (courtesy U. S. Army Air Corps)

(3) No appreciable uncertainty in the orientation of the cameras in azimuth or altitude need exist.

(4) Exposure-time is not restricted by motion of the camera.

(5) Fixed, identified stars provide a ready-made ground-control for orientation of the multiplex projectors and a reference-plane for measurements of parallax.

(6) More nearly automatic control of the camera-stations is possible. Exposures at the two stations may readily be synchronized by electrical means. Automatic searchlight control-devices provide the wherewithal for completely automatic orientation of the cameras, though economic considerations would be restrictive.

On the debit side are the following considerations:

(1) Lens-speed is important because of relatively low illumination of the subject. This factor is to some extent offset by the development of high-speed film.

(2) Instability and transitory nature of the aurora limits the exposure-time and requires simultaneity of exposures at the two stations; not a serious difficulty with intercommunication between stations maintained by radio or telephone.

(3) Unfavorable meteorological conditions may be included, because conditions making the aurora visible restrict the time of day, season of the year when photography is possible, and the geographical location of the sites selected.

(4) The direction of the stereo-base line may not always be most advantageous and, once chosen, it is immobile. But, with a net of at least three stations, flexibility in the choice of stereo-base can be attained.

(5) The aurora is not a fixed object having definite dimensions and boundaries. Therefore, precautions are necessary to ensure that exposure-times and sky-conditions are essentially the same at all camera-stations.

(6) The relatively high altitude of the aurora requires the use of a long stereo-base, if a favorable base-height ratio is to be realized. This factor tends to decrease the ease of continuous intercommunication between stations.

There appear to be several improvements possible in auroral photogrammetry through application of the technique of aerial topographical mapping. These are:

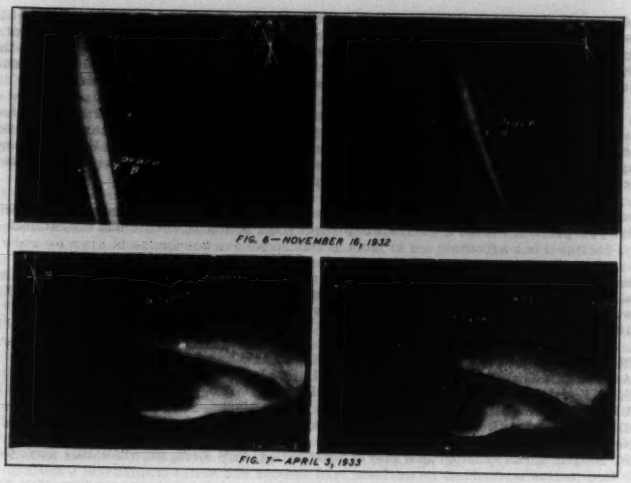
(1) The use of multiplex projectors to obtain a space-model of the aurora on a miniature but accurate scale. A more complete picture of the aurora is thus derived than through the calculations of heights and distances of discrete auroral points. Elevation-contours may be drawn directly to represent the third dimension--or it may even be possible to construct automatically a three-dimensional model.

(2) The use of modern improved lenses having a wider field designed to meet the exacting requirements of topographical mapping are incomparably superior to those used--at least by the author--for auroral work. Wide-angle lenses--up to 90°--which are now in use provide practically a distortionless image over the entire field. Six-inch lenses producing a negative of say nine inches diameter, in combination with high-speed film of fine grain, would produce detail and quality hitherto unobtainable. Though the necessary lens-speed for satisfactory auroral work is somewhat higher than for aerial photography, some of the present mapping cameras do have lenses of adequate speed. It should be noted, however, that an increased speed in lens or film is likely to be reflected by better definition in the photographs. The advantage of a greater field might well be partially sacrificed for higher speed, though in view of the great extent of the aurora, lenses of wider angle than previously used would be an important asset.

(3) Recent developments in emulsions make it unlikely that the ultimate, either in film-speed or quality, has yet been attained. Recent research in this field has not been publicized; and, in any event, results will not be generally available until after the war. There may even be by that time, color films having requisite speed. This opens up the possibility of recording auroral forms in color and perhaps their motion as well.

Through the elimination of the personal factor involved in processes such as tracing enlarged photographs and construction of the nets, and the employment of improved equipment, substantial reductions in photogrammetric errors may be anticipated. It is estimated that, under the most favorable circumstances, if a base-height ratio of 1:4 is realized, the total error in the location of an auroral point should not exceed 100 meters.

Two pairs of stereoscopic auroral views [4] are reproduced in Figures 6 and 7. The stereo-base is here 22.8 km, and the measured parallaxes of auroral points are of the order of 2° to 5°, with corresponding distances down to about 150 km. These are 20-second exposures, obtained with a Hugo-Meyer Kino Plasmat lens having an aperture ratio f:1.5 and a focal length of 50 mm.



Figs. 6 and 7--Simultaneous parallactic auroral photographs with stereo-base of 22.8 km, College, Alaska: (6) Homogenous band through zenith, November 16, 1932; (7) homogenous band, April 3, 1932

This lens, though of good quality and high speed, cannot compete with those now available. Cumulative errors, due to camera and projector, are shown as a function of distance from the optical center in Figure 8. For purpose of comparison, the dotted curve shows, on the same scale, corresponding errors for the aerial cameras and multiplex projectors used by the United States Geological Survey. The auroral camera was designed to accommodate 9 × 12 cm plates--on each of which six exposures were made. It is apparent that the size of image, here, is rather too small to secure the accuracy desired in photogrammetry.

Conclusion--Relatively little auroral research has been carried on outside of Norway, and this may be an opportune time for consideration of the merits of a long-range plan for further work in this field. Certainly such a plan offers ample opportunities for further contributions to scientific knowledge.

Application of recent technique and equipment--now in common use for aerial topographical

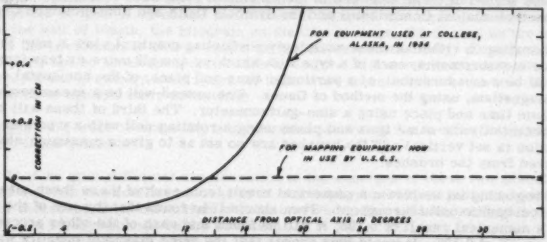

FOR EQUIPMENT USED AT COLLEGE, ALASKA, IN 1934
FOR MAPPING EQUIPMENT NOW IN USE BY U.S.G.S.
CORRECTION IN CM
+0.4
+0.2
-0.2
DISTANCE FROM OPTICAL AXIS IN DEGREES

Fig. 8--Distortion caused by lenses of camera and projector on scale 1 cm/° for equipment used at College, Alaska, in 1934, and mapping equipment now used by United States Geological Survey

mapping--to auroral photogrammetry promises results of educational and scientific value. High-fidelity lenses for cameras and projectors are capable of producing accurate scale-models of the aurora in space. Such models, directly obtainable, would have self-evident advantages over their imperfect synthesis from the results of rather laborious graphical or mathematical computation of discrete auroral points from parallactic measurements on photographic enlargements.

A new, or at least a refined, tool providing previously unattainable facility for studying horizontal extent and vertical penetration of ionizing corpuscles responsible for the aurora is at hand. Research on auroral-intensity distribution and its temporal variations within the E- and F-regions of the ionosphere would be facilitated. Such information would be of special value as an aid in the solution of certain problems concerning radio wave-propagation.

The compilation of a comprehensive and high-quality atlas of auroral forms, printed in two colors to give perspective, seems a worthwhile project from both a scientific and educational standpoint.

At present, photogrammetric facilities are reserved exclusively for urgent war work. Considering their adaptability to auroral photogrammetry and, in anticipation of their availability for other than war-time purposes, the author suggests that the scientific societies endorse a plan for their utilization in further auroral research.

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THE OERSTED AND THE GAUSS

F. Wenner

(Communicated July 7, 1944)

For more than 50 years there have been two schools of thought concerning magnetic quantities. The first of these maintains that induction and field are quantities of the same physical nature, and that permeability is a mere number, not a physical quantity. The second of these maintains that induction, field, and permeability are quantities, each of a different physical nature. For many years the first of these was in the lead and still has many ardent supporters. During the past ten or more years the second of these has been in the ascendency and has received the support of the International Electrotechnical Commission and the Symbols Units and Nomenclature Committee.

Before elaborating on either of these seemingly conflicting points of view it may be of interest to consider three measurements, each of a type with which we are all more or less familiar. The first of these will be a measurement, at a particular time and place, of the horizontal component of the Earth's magnetism, using the method of Gauss. The second will be a measurement at substantially the same time and place using a sine-galvanometer. The third of these will be a measurement at substantially the same time and place using a rotating coil with a commutator. The axis of the rotation is set vertical and the brushes are so set as to give a maximum electromotive force as measured from the brushes.

To make a beginning let us obtain a numerical result from each of these three measurements, using cgs electromagnetic units throughout. Then should it be found that the use of the method of Gauss leads to a numerical result of 0.195, it will be found that each of the other procedures leads to a numerical result of 0.195. It would thus appear that the same magnetic quantity was measured by each of these three procedures.

If now other units are used, regardless of how they are defined, other numerical results will be obtained. Furthermore, no two of these results will be the same, unless each unit is the same multiple of the corresponding unit of the cgs electromagnetic system of units. For example, in the GIORGI system of units the unit of length is the meter, the unit of mass is the kilogram, the unit of time is the second, the unit of current is the ampere, and the unit of electromotive force is the volt. In case the experimentally determined data are expressed in terms of these units, it will be found that the method of Gauss leads to a numerical result of 0.06166, the use of the sine-galvanometer leads to a numerical result of 195, while the use of the rotating coil leads to a numerical result of 0.0000195. Granting that the units used are self-consistent it would appear that more than one magnetic quantity is involved in these measurements.

It will thus be seen that the ideas of the first school of thought involve the use of a particular system of units, while the ideas of the second school of thought impose no such limitation. The concepts of those of the first school of thought are in accord with the ideas which were presented to us when we were in school and are expounded in most of the textbooks and treatises on electricity and magnetism. If one will use these concepts in measurements of the Earth's magnetism, he will conclude that a single magnetic quantity only is measured and that it makes no difference whether this is called field (or intensity) or induction.

The concepts of those of the second school of thought are in accord with the ideas: (1) That permeability is a physical property of matter or space, and is coordinate with density and electrical conductivity or permittivity; (2) that induction is a condition, existing locally, which manifests itself by a torque on a magnet, an induced electromotive force or current in a rotating coil, etc.; (3) that field is the tendency of a cause or causes located at a distance to produce an induction at the point (or throughout the small volume) under consideration. If one will use these concepts in measurements of the Earth's magnetism, he will arrive at the following conclusions: (1) In case a mechanical action is involved a magnetic quantity involved is the induction; (2) in case no mechanical action is involved a magnetic quantity involved is the field; (3) in case one part of a measurement involves a mechanical action and another part involves no mechanical action, both the induction and the field are involved.

Returning now to the three measurements with which we started, it may be concluded that the use of the rotating coil leads to a numerical result for the induction, that the use of the sine-galvanometer leads to a numerical result for the field, and that the use of the method of Gauss leads to a result which is the geometric mean of the results obtained by the use of the other procedures. This can be seen by a comparison of the results given for the case in which the GIORGI units were used. This is also in accord with a conclusion reached by Dr. HOWE (personal communication HHH).

Systems of measurements and units--Having made a few scratches on the surface of the philosophical aspects of magnetic measurements, it is in order to make a few remarks concerning systems of measurements and units. The only system of measurements, which will be considered here, is that system in which the basic quantities are length, mass, time, and magnetic permeability, and all units, whether mechanical, electrical, or magnetic, are defined in terms of standards of these four quantities.

In case the unit of length is taken as the centimeter, the unit of mass is taken as the gram, the unit of time is taken as the second, and the unit of permeability is taken as the permeability of free space, definitions of units of magnetic quantities present no complications. However, the definitions of the commonly used units of mechanical and of electrical quantities involve, for the most part, a power of ten. If we should follow recent International recommendations, we would use the meter as the unit of length, the kilogram as the unit of mass, the second as the unit of time, and 10^7 times the permeability of free space as the unit of permeability. Then powers of ten would, for the most part, not be involved in definitions of units of either mechanical or electrical quantities. However, if the presently used magnetic units were to be retained, it would be necessary to introduce powers of ten into their definitions.

Suggestions--If I were to make any suggestions concerning the broader aspects of magnetic measurement, these would be:

(1) That we give sufficient consideration to the concepts of these two schools of thought to understand that the conflict of ideas is of a metaphysical nature and has nothing to do with magnetic measurements, other than what is involved in the well-known fact that the numerical part of a result depends on the unit used.

(2) That we use a system of measurements in which the basic quantities are length, mass, time, and permeability, and use units all of which are defined in terms of standards of these four quantities.

(3) That in stating results obtained in magnetic measurements we use cgs mu_0 units rather than the GIORGI units.

(4) That we use the oersted as a name for the unit of field and the gauss as a name for the unit of induction.

It is to be noted that suggestions (2) and (3) are in accord or at any rate not in conflict with present practice of geophysicists; also, that suggestions (2) and (4) are in accord with recent International actions, while suggestion (3) is not.

References--A systematic discussion of the basic ideas of the first school of thought will be found in almost any textbook or treatise on electricity and magnetism. What is probably the best discussion of the subject is given in a paper by RAYMOND T. BIRGE [Amer. Phys. Teacher, v. 3, p. 171, 1935].

A systematic discussion of the basic ideas of the second school of thought apparently is not in existence. What probably is the best available discussion of this point of view is given by E. G. CULLWICK in Fundamentals of electromagnetics [Camb. Univ. Press].

An understanding of the present state of confusion of ideas concerning electric and magnetic quantities may be gotten by reading pages 782 to 859 inclusive of Electro-magnetics, a discussion of fundamentals, by ALFRED O'RAHILLY [Longmans, Green, and Co., Cork Univ. Press].

Department of Terrestrial Magnetism,
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Washington 15, D. C.

AMERICAN GEOPHYSICAL UNION

TWENTY-FIFTH ANNUAL MEETING

PART IV

SECTION OF OCEANOGRAPHY

REPORTS AND PAPERS

Washington, D. C.
June 1, 1944

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THE OCEANOGRAPHIC ACTIVITIES OF THE HYDROGRAPHIC OFFICE DURING THE PAST YEAR

G. S. Bryan

While it is natural to think of war as a great destructive force tearing down the advances in science made by man, paradoxically, it is during such a cataclysm that the sciences which have contributed so greatly to the progress of humanity receive their greatest impetus. This is especially true of oceanography, and particularly in the case of the United States Navy.

In normal times, while the Navy cooperated with the various scientific bodies in furnishing data, whenever obtained, its interest had, for the most part, been mainly passive. However, with the outbreak of hostilities, the true importance of oceanography as a factor in the successful conduct of the war was realized. Naturally the burden of furnishing the forces afloat with all available information fell upon the Hydrographic Office. Fortunately, the Office had for years maintained close liaison with such institutions as the Scripps Institution of Oceanography, the Oceanographic Laboratories, and the Woods Hole Oceanographic Institution. This close association was of invaluable aid in the coordinating of a program to supply the information expeditiously. The Hydrographic Office was fortunate enough to obtain the services of ROGER REVELLE, who is now a commissioned officer in the Navy, and working with us. Under his able leadership, competent personnel were assembled to attack the various phases of oceanography as they related to actual military operations.

Within the Hydrographic Office, during the past year, an Oceanographic Unit has been set up. While, for security reasons, I am not at liberty to disclose the nature of its investigations, I can say that no major operations are undertaken that do not have the benefit of the oceanographic studies made by this unit, and their reports have contributed greatly to the success of the operations.

While primarily established to aid in the war effort, the unit is making an important permanent contribution to the advancement of oceanography, and it is my intention to continue an Oceanographic Unit in the permanent organization of the Hydrographic Office after the war. This unit has done a fine job, and has demonstrated the importance of its work to the Navy in war time.

During the past year much progress has been made in the series of ocean surface-current charts being compiled by the Office. Monthly charts for the North and South Atlantic oceans, the Indian Ocean, and portions of the North and South Pacific oceans have been completed and published. These charts show the resultant set and drift of the current within each one-degree quadrangle over the ocean areas. It is planned to incorporate five-degree current roses showing the stability of the currents on future editions of these charts. On account of the war they are not available for general distribution, but when peace returns they will be available in atlas form. An atlas of this type has already been prepared showing surface temperatures throughout the world. A similar series of ocean "Sea and swell" charts has also been prepared. These charts show graphically by means of roses the direction and percentage of frequency of the low, medium, and high sea-and-swell conditions that have been observed over a period of many years in the various ocean areas. These charts will also be made available in atlas form after the war.

These series of charts give a glimpse of the oceanographic activities that are engaging the attention of the Hydrographic Office at the present time. They represent only a fraction of our work. I wish that I could expatiate on the other vital services that are being rendered to the Navy by the Hydrographic Office, aided by the oceanographers who are so ably contributing their knowledge and experience to the various projects, but I know that you all realize my position, for many of you are employed in their furtherance, and understand that success depends upon the maintenance of secrecy.

The far-flung scale of naval operations, as a result of the war, is bringing to the Hydrographic Office a wealth of material covering waters not normally traversed by shipping. These data are a welcome accession as they shed light on those regions so poorly covered in the past. When correlated with existing information, they will help weave the clear pattern of the orderly forces of natural phenomena as they relate to oceanography. Much of the research must necessarily await the termination of the war, but, in the meantime, every item of intelligence that will contribute to the eventual victory is being utilized.

Surveys are being continued by the Hydrographic Office in increasing numbers; soundings in previously poorly sounded areas are being obtained; and charts of many new areas are under construction. New and improved methods are being developed in the technique of surveying and navigation, as well as in production of charts. The vast increase in the work of the Hydrographic Office may be judged from the fact that the production of charts of all kinds for the fiscal year ending June 30, 1944, will approximate 45,000,000 copies.

I wish particularly to express my appreciation to those agencies and scientific societies affiliated with the American Geophysical Union who have assisted the Hydrographic Office in carrying out this work. Without their help, we would never have been able to carry out our program. This is particularly true of the Oceanographic features, and I hope that we may be able to reciprocate after the war by supplying oceanographic data which is needed by them.

When our enemies have been defeated and our labors during these trying times may be freely discussed, I think it will be revealed that the Hydrographic Office and the scientists associated with it have rendered to our Navy and to the cause of civilization a service that not only hastened the ultimate victory, but made a lasting contribution to oceanography.

U. S. Hydrographic Office,
Washington, D. C.

OCEANOGRAPHIC ACTIVITIES OF THE UNITED STATES COAST AND GEODETIC SURVEY

L. O. Colbert

The curtailment of the oceanographic activities of the United States Coast and Geodetic Survey because of war conditions has been continued for the past year. All offshore operations which were under way before the war have been discontinued and all hydrographic surveys are now being limited to areas near the coast and in harbors and intracoastal waters. All these surveys are in strategic areas and are being made at the request of the armed forces.

In view of the confidential nature of this work, references to localities cannot be made.

To replace one of the large surveying units transferred to the Navy for the duration, the Navy has transferred to the Coast and Geodetic Survey for urgent surveys a wooden vessel, the Derickson, now nearing completion in the United States.

Development work has continued on our new radio current-meter. The MV E. Lester Jones during the past winter has continued the current survey in Puget Sound begun several years ago. Several of these radio current-meters with their stream-lined buoys are being used and four additional meters have been ordered from the manufacturer. The radio current-meters have now reached the stage of development which shows the decided advantage over old methods by furnishing observations at several stations by the use of only one observing unit.

During the past summer intensive current-surveys have been made with these meters and buoy-equipment in two areas on the Atlantic Coast which were requested by the Navy.

Another current-survey not involving the use of the radio current-meter was also carried out in a third important area on the Atlantic coast to obtain detailed data for the use of the Navy.

In the field of tides, application of observational data to special problems relating to war activities continued to be emphasized. Analyses were made of new records obtained from outlying bases and occupied areas, where their need for the operations of the armed forces was urgent. The existing system of primary tide-stations was continued in operation within the limits of war-time restrictions.

The program of cooperative tide-observations in Central and South America was continued without further expansion. As a result of these observations the tide-tables now contain daily predictions for 12 additional ports between Mexico and the Strait of Magellan.

Processed publication TW-1, "Water temperatures, Atlantic and Gulf coasts (May, 1940)" has been superseded by TW-1 (Revised), "Surface water temperatures, Coast and Geodetic Survey

tide stations, Atlantic and Gulf coasts." The tables in the revised edition have been rearranged to give additional information and the data extended to include observations through 1942.

U. S. Coast and Geodetic Survey,
Washington, D. C.

RESEARCH WITHIN PHYSICAL OCEANOGRAPHY AND SUBMARINE GEOLOGY AT THE SCRIPPS INSTITUTION OF OCEANOGRAPHY DURING APRIL, 1943, TO APRIL, 1944

H. U. Sverdrup and Staff

(Contribution from the Scripps Institution of Oceanography, New Series, No. 257)

Again there is little to report to the American Geophysical Union because nearly all the activity in physical oceanography at the Scripps Institution has been in connection with special war projects and results can not as yet be discussed.

G. F. McEWEN has critically reviewed manuscripts and earlier publications in order to indicate appropriate corrections and revisions. For example, extensions of his work on evaporation and mixing, published in 1929, require a computation of the preliminary mathematical tables in the appendix of that work with the aid of newly developed formulas and the extensive fundamental tables recently prepared by the Federal Works Agency (Mathematical Tables Project). This computing is more than 95 per cent completed and the tables may be of use in other researches.

Again, a manuscript is in preparation on the relation of surface ocean-currents to surface temperatures. This is designed to serve as a guide in making extensive applications later, and will include all necessary tabulations and working diagrams.

In compliance with requests for extending the tables by McEWEN in his publication on the Significance of differences (1929), certain practicable methods have been explained of approximating to the results desired for values of the numbers of observations not included in the publication. This year, new and accurate methods of making such computations have been developed that depend upon the tables by PEARSON on the Incomplete beta-function, recently available. Either mimeographed or printed copies of this supplementary paper will soon be prepared.

Regarding the problem of horizontal dispersion of material from an initial source, circular in form, a new and much more satisfactory solution has been obtained, having an error of less than one per cent. This method can be readily applied with the aid of tables or diagrams to be prepared.

The usual observations of temperature, salinity, and weather at our six shore-stations and supplementary observations from United States lighthouse tenders have continued. There were about 1800 salinity observations, 1800 sea-temperature observations, and 1500 wind-observations. Continuous barograph- and pyrheliometer-records and daily observations of humidity and precipitation were maintained at the Scripps Institution.

E. G. MOBERG reports that owing to the lack of laboratory assistance and facilities for obtaining offshore observations or water-samples no important amount of laboratory work has been done. However, nearly all the working space, as well as much of the laboratory equipment, has been in nearly constant use by other members of the Institution's staff or by visiting investigators, to some of whom advice or assistance has been rendered. One of the laboratories, together with apparatus and supplies, has been used by V. SCHEFFER (until January) and Mr. SENN of the United States Fish and Wildlife Service in conducting research on the preparation and properties of agar, the constant-temperature room has been used by C. K. TSENG in carrying out experiments on the growth of Gelidium under controlled conditions of light and temperature. The carbon-dioxide changes in the growth medium of the Gelidium during these experiments were measured by Mrs. SWEENEY who was provided with laboratory space and apparatus for this purpose.

Throughout the year work has been done on field- and laboratory-data previously obtained and it is expected that in the near future some papers based on these data will be ready for publication. Among the subjects dealt with may be mentioned potentiometric methods for determining the salinity of sea-water; the variation, local and according to depth, of the calcium-content of sea-water in several extensive areas of the northeastern Pacific Ocean; and the dynamical and chemical material resulting from the cruises in 1941 of the E. W. Scripps.

Scripps Institution of Oceanography, University of California,
La Jolla, California

THE BATHYMETRY OF THE CENTRAL AMERICAN REGION, WEST COAST OF MEXICO AND NORTHERN CENTRAL AMERICA

H. T. Whitcroft

During the past year a bathymetric study has been made of that part of the Pacific Ocean off the Coast of Mexico and Central America in conjunction with the revision of charts of the Hydrographic Office of that area. This section of the Pacific Ocean on which nothing has been published is a necessary part of any study of the Western Caribbean Area. The bathymetric charts of the Pacific Coast of Central America and Mexico published prior to 1912 depict an indefinite, steep foreshore delineated by very few soundings. The chart of the Pacific Ocean by Dr. M. GROLL of the University of Berlin (1912) gives more detail, the first to show two narrow trenches along the west coast of Mexico opposite the town of Acapulco, with a depth of 5,341 meters and 5,120 meters.

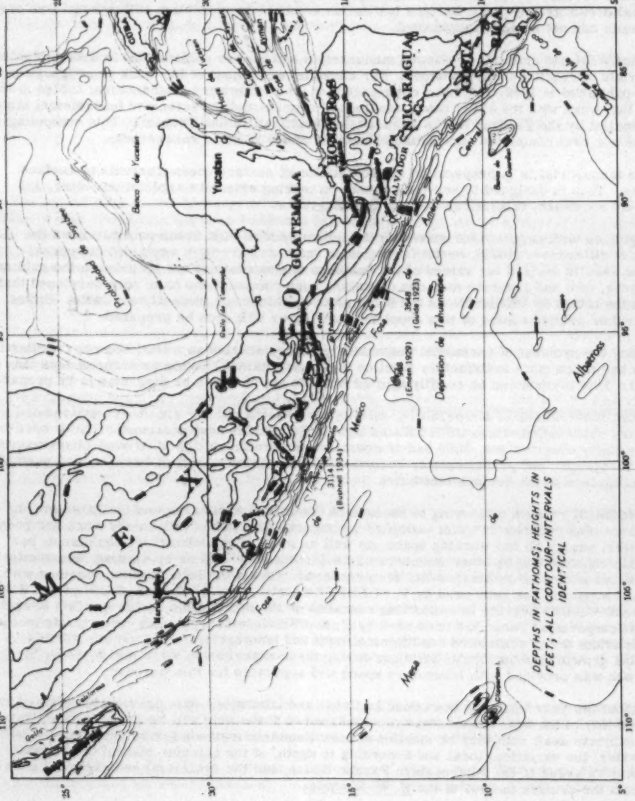

Fig. 1--Bathymetric chart of Pacific and Atlantic oceans off coasts of Mexico and Central America

This same chart outlines a large shallow depression off the Gulf of Tehauntpec, the northern edge of which follows a line more or less as can be delineated today. There was, however, no indication of the deep trough in shore off the Gulf of Tehuantepec.

In 1923, the United States Coast and Geodetic Survey Steamer Guide, while en route between the east and west coasts of the United States, discovered the water-deep off the Gulf of Tehauntepec. This discovery was first published by Captain HECK of the Survey in the Bulletin of the Seismological Society of America. It was about this time that the United States Navy started its work on deep-ocean development by ships en route from port to port. Today, all ships cruising along the west coast of Central America have reported thousands of soundings in this area and from these reports this bathymetric development was made. Though not completed, this development gives a good idea of the general size and shape of the major features along this coast.

(Accepted names have been used when they existed but many new names have been added. The use of the words "trench" and "trough" have not been used in the exact sense as defined by the Committee on Nomenclature. The new names and the departures from the definitions have been used primarily for describing and not for any controversial reason.)

The bottom of the sea off the western coast of Central America and Mexico is a large plateau extending some 700 miles offshore with a deep narrow trench close inshore. The Murray charts of the bathymetry of the Pacific show a 2,000-fathom plateau around the point of lower California named the Californian Plateau and another around the Galapagos Islands which MURRAY calls the Galapagos Plateau. The present development by ships of the United States Navy shows that these two plateaus are connected. This feature was first delineated on the Hydrographic Office "Bathymetric Chart of the North Pacific" and the name Albatross Plateau (Mesa de Albatross) used. The surface of this feature is generally level, broken by very small rises and depressions varying only a few hundred fathoms each side of the 2,000-fathom depth. The large depression off the Gulf of Tehuantepec (Depresion de Tehuantepec), the Cocos Island Ridge (Cumbre de Isla del Coco), and a short protrusion of a 1,000-fathom curve from the southern extremity of the Republic of Panama are the only exceptions. Most interesting is the practically continuous trough close inshore extending from a point off Cape Velas in Costa Rica to a point off Maria Madre Island at the mouth of the Gulf of California, a distance of more than 1,400 miles. The boundary of this feature was considered to be the 2,000-fathom curve and, although off the coast of Guatemala, it departs from the narrowness necessary to define a trough but the 2,500-fathom trench carries the feature through this area. This feature can definitely be divided into two parts, the Mexican Trough and the Central American Trough.

The Mexican Trough (Fosa de Mexico) extends along the coast of Mexico from a point off Port Angeles to a point off Maria Madre Island at the mouth of the Gulf of California. Throughout the whole distance the continental shelf is practically non-existent. In the northwestern part we find three small trenches which conform in direction to the trend of the coast-line, while at the southeastern end is a large deep depression defined by the 2,500-fathom curve to which the name Acapulco Trench (Trinchera de Acapulco) has been applied. It extends from longitude 93° 30′ west to 102° west in the Mexican Trough, a distance of about 280 miles. The axis of this trench and also this section of the Mexican Trough bears 290° true. The greatest depth reported was 3,114 fathoms by the U.S.S. Bushnell, now a survey-ship of the Hydrographic Office, in 1934 at a point southwest of Acapulco. This feature is approximately the same as that which appears on the early German charts and to which the name Apapulco Deep had been applied. Dr. SCHUCHERT appears to have confused this deep and the deep discovered by the Guide in describing the ocean bottom off this coast [Schuchert, Historical geology, Antillean-Caribbean Region, p. 320].

The Central American Trough (Fosa de America Central) is a rather narrow and deep feature extending from a point inshore of the Mexican Trough off Port Angeles in a southeasterly direction more or less straight to a point off Cape Velas in Costa Rica, a distance of 600 miles. The extreme eastern end of this feature as bounded by the 2,000-fathom curve veers rather sharply to the south conforming with the shore-line of the coast of Costa Rica. The continental shelf throughout the whole distance is comparatively wide when compared with the practically non-existent shelf off the coast of Mexico.

The deep portion off Guatemala has been named Guatemala Trench (Trinchera de Guatemala) on all recent bathymetric charts. The narrow 2,500-fathom section with the three 3,000-fathom deeps, to the east of Acatenango Canyon, could easily be classified as a separate feature. This section is on the same straight line and the same bearing as the Acapulco Trench. An interesting observation is that that part of the Central American Trough to the west of a point near the Acatenango Canyon (Canon de Acatenango) deflected northward at an angle of about 3° displacing ex-

treme western end 25 miles shoreward of the Mexican Trough. The data used in delineating this feature are not as complete as we would like but it is felt, from the information on hand, that the 2,000-fathom curves of the two troughs do not connect at this point.

There are many details that no doubt would have a geological significance which can not be thoroughly described due to lack of sufficient information. The largest of these, the Tehuantepec Depression (Depresión de Tehuantepec), seems to be of special interest. The northwest edge is more or less along the same continuous line as the line of volcanoes across the Isthmus of Tehuantepec. The 988-fathom spot on this line discovered by the Emden in 1935 might also be a volcano beneath the ocean surface. There are many canyons apparently of the same nature as those off the west coast of the United States throughout the distance of the Mexican Trough. There is sufficient evidence to outline one at the Gulf of Dulce and a peculiar arrangement of two canyons off Acapulco.

Some of the many questions that are brought to mind after examining this bathymetric development are:

(1) Is there any correlation between the parallelism of the east and west edges of the Tehuantepec Depression as defined by the 2,000-fathom curve and the Cocos Island Ridge?
(2) Can the Guardian Bank be given a geological explanation?
(3) Is there any relation between the Cayman Trench and Acatenango Canyon?
(4) What is the significance of the apparent displacement of the Guatemala Trench and does the volcano and Canyon of Acatenango fit into this displacement?
(5) Is the existence of the Techuantepec Depression a down-fault similar to the known down-faulting of the Isthmus of Techauntepec?
(6) Is it possible to correlate the Albatross Plateau with that hypothetical land-area supposed to be west of Mexico which could have caused the deep inshore-trench?

It is felt that the intensive bathymetric development of the Caribbean Sea and the Gulf of Mexico was not complete until a development was made of the Pacific side of the Republic of Mexico and Central America. This present development has brought forth some interesting features of the ocean bottom that would well merit a more intensive development which must wait until some other time when our Navy is not so actively employed in the prosecution of the tremendous task of victoriously ending the present conflict.

U. S. Hydrographic Office,
Washington, D. C.

BATHYMETRY OF THE PACIFIC

Henryk Arctowski

During the ice-ages the formation of extensive inland-ice caps took up a certain amount of water from the oceans and thus the sea-level should then be slightly lower, and shore-lines should retreat seaward.

On the contrary, the overcharge of the glacial areas, in the case of a perfect isostatic equilibrium, should cause a sinking of the land, an advance of shore-lines, and evidently an uplift at a certain distance from the inland ice. Such a possible cause of sea-level variations has been frequently discussed.

In the case of the Antarctic Continent, where, during the Pleistocene, an even more extensive glaciation than at present must be admitted, the continental shelf (at least in the region of the Belgica Drift) extends to a depth of 600 or 700 meters--an abnormal depth.

If, in pre-glacial times, the isobath of 200 meters may have been the demarcation of the edge of the continental shelf, a 400-meter downfall of the continent, due to the weight of the inland ice, is admissible.

Pre-glacial changes of sea-level, such as extensive transgressions, may have been due to continental orogenic causes as well as to changes in depth of sea-bottoms.

It was 50 years ago, while still a student, that I was greatly impressed by the Cretaceous marine deposits of Hokai, at an altitude of 565 meters, on top of the abraded Hercynian Mountains

of the Ardennes, in Belgium. Tertiary deposits of the transgressive Tongrien also extend to an altitude of 460 meters, near Houffalize [Bull. Soc. Géol. de France, 1895]. It seemed to me that it must have been the sea-level which rose and descended and then rose and descended again probably millions of years later.

I do not know whether a geological chronology of transgressions has been compiled. But since some of these changes of sea-level seem to have been geologically contemporaneous all over the world, their cause must have been bathymetric.

The Arctic Ocean is but a basin. The Indian Ocean is the product of a downfall of parts of Gondwana. The Atlantic has a submarine ridge extending from north to south. The Pacific is of a complex nature; arcs of islands and deep trenches all due to some push, from the north, between Alaska and Kamtshatka, from the west in front of Asia, from the southwest and the northwest in front of Australia, and from the south in front of the Antarctic Continent.

Avoiding the problems of the old primitive continental cores, the Laurentia and Angara, resisting compression during all the consecutive geological ages, the Brazilian core and those of Africa and Australia, probably Antarctica as well, avoiding even the mention of the old mountain chains, I only wish to bring to your attention the two main directions of the Tertiary foldings west-east through Europe and Asia, and north-south along the Pacific coasts of North and South America, and then also the loops between North and South America and South America and the Antarctic Continent--all this simply to show that they seem to be nothing other than the geographical picture of two distinctly different results of push from the west towards the east and from the south towards the north. The shrinking of the Earth's crust along the Himalaya Line was insufficient; the volcanic Sunda Islands had also to show a bending.

And now with all such evident signs of orography due to major displacements, two questions should be asked and answered if possible:

(1) Are the foldings and crackings of the Sial due to a shrinking of the Sima at depths of 30, 45, or 70 km?
(2) Do the strata beneath the oceans react first to the shrinking of the Sima?

Any sub-oceanic earth-crust deformation must directly affect the sea-level all over the world.

The formation of the mid-Atlantic Ridge should have been the cause of important transgressions. The same for the circum-antarctic swell. The subsidence of the Indian Ocean gave more room to the hydrosphere and might have been the cause of important regressions, might also be the cause of the cracking of the African Continent. All of it may have been connected with the Himalayan Foldings.

The area of the Pacific, this large area surrounded by the "circle of fire" of RECLUS, is certainly the most interesting to study. Here volcanologists and petrographers already dispose of all the necessary data for synthetic considerations. Seismological and gravimetric data are at hand and it remains only for oceanographers to induce the hydrographers and the United States Government to make a final conquest of the Pacific, toggive us bathymetric maps as perfect as possible, leaving no areas in blank, so that it may be possible to trace correctly the lines of foldings and of presumable fault-lines.

Then, and only then, will it be possible to know whether the Asiatic deep-rooted Sial has been pushed over the Pacific Sima, or whether the big trenches in front of the areas of over-thrust have been the cause of regressions of sea-shores, the cause of the existence of more land to live on.

Smithsonian Institution,
Washington, D. C.

FUTURE ACTIVITIES IN DEEP-SEA SURVEYING

T. H. Whitcroft

(This article is the author's own conception of the problem of oceanic surveying and not any policy of the Hydrographic Office)

When we consider the tremendous expanses of the some 140,000,000 square miles of ocean--four-fifths of the Earth's surface--and then speak of bathymetric development of this area, it is staggering. Forty years ago, it was not considered within the realm of possibility, but today we can see into the future a time when ocean bottoms of the world will be much better developed than they are now. However, to accomplish this, a plan of action must be worked out wherein all agencies with the equipment and ability can be working in cooperation toward a common end.

The study of the ocean basins has to this time been possible only because of the interest the maritime nations have in soundings for their navigational charts. It is only natural for the scientist to be interested in the problem offered by this unknown frontier of which so little is known. Our knowledge to this time has been supplied by lines of soundings from ships cruising on other missions. These lines of soundings along the ocean routes of the world can easily be considered a reconnaissance. Much of the ocean area need not be developed further than this because of uniformity of the bottom. These reconnaissance-data give us the location of special features which warrant a closer development. The problems at this period in the development of the ocean basins, therefore, are: (1) To secure the necessary soundings; (2) to evolve a more uniform method of correlating and publishing these soundings on an International basis; and (3) to agree upon a more suitable means for graphically representing these soundings.

How more soundings can be secured

There is proposed a change of the regular Navy log in order to give better meteorological information. A part of this new log will request hourly depths from all ships at sea. If accepted, this will greatly increase the sources of data to the United States Hydrographic Office. This same plan might also be required of merchant vessels. Should a plan of daily or hourly reporting of soundings similar to the plan proposed above be instituted by other maritime nations, this would be an additional source of sounding data. A plan could be arranged whereby the United States Government might furnish merchant ships with deep-depth sounding equipment on a rental basis. Reports of the soundings taken over the courses traversed by these ships could be accepted as payment for the rental of this equipment. After the war, no doubt, there will be many deep-depth sounding machines in ships that will be tied up. The rehabilitation of the various countries of the world will cause a tremendous amount of ocean-going traffic. This traffic will not be hindered by submarine warfare, neither will it be limited as to time of passage. These two factors would offer an opportunity of covering many unsounded areas close to the regular ocean routes if proper plans were made now. One proposal would be to bring up to date the "unsounded-area" charts of the Hydrographic Office.

One of the big problems confronting the development of the ocean basins is, in the final result, a lack of funds. The tasks to be performed are of such magnitude and fraught with so many difficulties that governmental agencies are the ones best equipped to do this type of work, most notably the United States Navy. Funds are just as necessary to these governmental agencies as they are to private enterprises. The moneys are set aside by appropriations which are voted on by political bodies. These political bodies depend upon the general public for their support. The lack of understanding by the general public serves to breed lack of interest, thus making the securing of appropriations very difficult. An interesting example of what understanding can accomplish is the development of the Caribbean by the United States Navy. This was made possible by Dr. H. H. HESS' efforts in arousing the interest of the United States Navy by making the problem understood. There should be some program to arouse the interest of the general public in the oceans. The oceans are not large areas bounded only by islands and continents, but are complex submerged land-forms of mountains and plains. When more laymen desire fuller knowledge of the oceans, the securing of grants for a more thorough study will be a much simpler task.

The cataloging and indexing of soundings

There is definitely expected an increase in the volume of soundings in the future, and when this happens a decision must be made on some method of processing these soundings so that they can be of use. To date this processing has been handwork and should the volume increase we would be forever behind which, therefore, will entail much necessary work. As years go by and the data

accumulate, the magnitude of our task can be very aptly illustrated by a request made of the United States Coast and Geodetic Survey some years ago. In the December, 1937, issue of the Field Engineers Bulletin of the Survey appears the following article:

"I want for my work the number of feet depth for at least every square mile of ocean surface. Please designate location of each depth by longitude and latitude. I would be pleased to have soundings for all inland seas, gulfs, etc., that is, all land which is covered by water all over the world

"P.S. I do not require depths of rivers or lakes." (End of letter)

"Let us suppose for the moment that data are available to fill this modest order. If the answer could be typed on letter-size paper of standard weight, averaging 230 sheets to the inch, and the typing single space, with each depth and its corresponding position on a single line across the page, it would permit the tabulations of 50 depths to a sheet. Since the water-area of the world is, in round numbers, 140,000,000 square miles, the required tabulation could be crowded on to 2,800,000 sheets.

"The slide-rule furnishes some rather startling facts relative to this sizable paper-requirement: Stacked in a single column, its 1,014-foot height would dwarf the Washington Monument by 459 feet; the cost of the paper alone would exceed $2,000; and its weight of 15 tons certainly would irk the postman delivering the reply. At a rate of 1,000 depths per day 383-1/2 years would be required to scale and tabulate the data."

These statistics approach the impossible, and when we add to that the labor inyolved in the reduction of these soundings to meters and fathoms and also for salinity and temperature it seems more so. But I do feel that by use of modern machines it is possible to do a task of this magnitude.

I have been working for the past few years on a machine-method of cataloging, indexing, and plotting of oceanic soundings that would be uniform and would be acceptable on an international scale.

At present, each country that publishes "Deep-sea sounding lists" uses a different method. The British publish soundings reduced for salinity and temperature only; the Germans publish the recorded depth and the reduced depth; and the United States Hydrographic Office publishes only the recorded depth at a definite calibration. The arrangement in these publications is as good as could be expected with individual nations publishing their own data, in that it is received in continuous lines of soundings. This arrangement of continuous lines of soundings causes much effort and confusion when plotting the soundings of any given area, because one must search several publications and many individual pages in each publication to secure the necessary soundings.

It is reasonable to assume that in the future our receipts of oceanic soundings are going to increase. When this happens, and if the present system of publication is used, the data will be in such bulk and in such a state of confusion that to secure the deep-sea soundings necessary to construct a chart it will almost be necessary to visit the various agencies where the needed data are filed and dig them out. One reason that oceanic soundings are not published by the Hydrographic Office is the expense involved and the great amount of time necessary to prepare the publication. This, no doubt, is true in many countries which before the war published sounding data, and also those countries that never published any.

After studying the publications of other nations, the following plan was devised whereby, with sufficient International cooperation, all oceanic data throughout the world pertaining to deep-sea soundings could be published periodically in an accurate, flexible, and economical manner. This plan or system is arranged so that all agencies will receive all sounding data in a manner that is acceptable to them.

Mr. VANNESS and Miss KERBY of the Washington Office of the International Business Machines Corporation, have spent much time in arranging the data so that the end-result would satisfy the conditions mentioned above--accuracy, flexibility, and economy. This system, as presented, is not final and it is possible to make changes in both the recording of the data on cards and the tabulation of the data for publication.

The proposed system as worked out is as follows:

First step: Each country that receives oceanic soundings will transfer these data to punch-cards--The only data manually entered on each card will be the latitude, longitude, and recorded depth, with the rest of the necessary information from the report being added automatically by the same machine. The original data should be checked over by a hydrographic engineer for accuracy,

dependability, and clearness. Should the report not be too complicated in its presentation, the average operator could enter approximately 1,600 soundings per day, and these entries could be verified by another operator at approximately 2,500 soundings per day.

These cards now contain the following information: (1) A serial number for each report; (2) the country receiving the report; (3) the type of ship; (4) the name of ship; (5) the calibration of the sounding machine; (6) the surface temperature; (7) the month and year of the sounding; (8) the recorded depth; (9) the latitude and longitude.

The surface temperature and the month and year of each sounding are partially automatic. The recorded depth and the latitude and longitude are manually entered for each sounding. The remaining data for each sounding are automatically entered by the same machine. It is interesting to note that it is with this operation that the only chance of human error enters into this system.

Second step: All cards sent from original agency to one central agency for processing--The processing is as follows:

(A) The cards containing the sounding data are assorted so that they will be separated by latitude and longitude into the areas as delineated in the "British Admiralty tables of velocity of sound in sea water." The number of the area is then automatically punched into each card.

(B) Then, in each of these areas, the cards are assorted according to depth-layers. Then the true velocity for area and depth-layer, as recorded in British Admiralty tables, is entered automatically on all cards.

(C) With the true velocity and the calibration of the sounding machine on the cards, they are reassorted as to similar calibrations. Then the true velocity is divided by the calibration and the result (corrective factor) is entered on the cards. This operation is also automatic.

(D) This corrective factor is then multiplied by the recorded depth and the resultant--the sounding reduced for salinity and temperature--is then automatically punched into the card.

(E) The cards are again assorted into meter- and fathom-groups, then automatically multiplied so that the recorded and the reduced soundings are punched into the card in both meters and fathoms.

Third step: Arrangement of cards--The cards are arranged in any system and the data of each card automatically tabulated on a sheet which can be bound into a book. The data that may be used is as follows: (1) The report number; (2) the original agency; (3) calibration of the sounding machine; (4) date; (5) surface temperature; (6) latitude and longitude; (7) recorded depths in fathoms and meters; (8) depth, reduced for salinity and temperature, in fathoms and meters.

Fourth step: Reproduction of tabulated data--The tabulated data are reproduced by photolithography from the sheets of tabulation and distributed in loose-leaf form to the contributing agents. The advisability of some method of loose-leaf publication is that the accessions as they are received can be added to the accumulated data and same areas will always be together.

Notes--It might be advisable to arrange all back-logs of oceanic soundings on a uniform basis. Should the above plan be accepted, all deep-sea sounding data would be in one form. It was estimated that this back-log of soundings in the Hydrographic Office could be entered on cards and tabulated for publication in one year at a cost of about $6,000. The accumulation of soundings by other nations can be estimated to be about one-half that of the Hydrographic Office.

In average years, the United States Navy would add approximately 50,000 soundings annually. It is estimated that the larger countries like Great Britain, Germany, Japan, France, and, perhaps, Norway and Sweden, would add the same amount per country.

Advantages--(1) The original document stays with the agency which receives it; (2) the recording of the data is economical and correct; (3) all calculations done in a central agency in bulk, making for a more economical handling; (4) new data arranged by area; (5) all oceanic data of any given area readily available for any type of cartographic work within an area; (6) the whole of the data, being received at definite periods, will make it easier to keep charts up to date; (7) the published data will supply the information in a form which would satisfy any agency. There are four remaining spaces which on the punch-card could be used to show the chart on which the soundings were plotted, and marked thus: Plotted on Chart No. ____. This would assist the cartographers in selecting soundings from the tabulated list which would be consistent with the charts of other countries.

Bathymetric charts and projections

The bathymetric data on navigational charts are of little use today except from the standpoint of interest and this will be more true as time goes by. As we advance in knowledge of distance-finding through the water and through the air, the use of bathymetric features will become more and more geophysical and less and less navigational. With this thought in mind, the Committee could promote the idea of producing bathymetric charts by various nations on some uniform conformal projection. This will give the ocean-bottom geography in a manner that represents the shape more nearly as it is on the Earth's surface.

In that the continents proper extend beyond the shore-lines to the foot of the Continential Slope, it might be advantageous for the series of geological quadrangle-sheets to be extended to cover the Continential Slope.

A very confusing aspect in the study of bathymetric charts of various nations is the shifting from meters to fathoms of the isobathymetric lines. This is especially true in describing features. A definite feature may be described and delineated from a study made in meters, but when translated into fathoms, the feature is not outlined by a curve. An example of this is the Pennell Bank in the Ross Sea. Regardless of what system of measurement is used--meters or fathoms--in the construction of a chart, the isobathymetric lines could be delineated in any other system.

U. S. Hydrographic Office,
Washington, D. C.

AMERICAN GEOPHYSICAL UNION

TWENTY-FIFTH ANNUAL MEETING

PART IV

SECTION OF VOLCANOLOGY

REPORTS AND PAPERS

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EARLY HISTORY OF THE MEXICAN VOLCANO PARÍCUTIN

Parker D. Trask

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United States Department of the Interior)

Owing to the good fortune of being stationed near the new volcano Parícutin when it first erupted, I was able to visit it when it was only a week old. As my observations have been recorded in full in a previous article [see 1 of "References" at end of paper], only a few of the more pertinent features are repeated here, in order to give a setting for the succeeding papers in this symposium.

The most significant feature about this volcano is that it started from a plowed field in a region in which no previous volcanic activity had been recorded within the memory of man, which in that area goes back for several hundred years. However, the country is a scene of much volcanism in the not remote geologic past, as several hundred cones are found within a radius of 50 miles of Parícutin.

The location of the volcano is on the east side of the main range that forms the west boundary of the central plateau of Mexico, some 200 miles west of Mexico City. It is a region of cultivated lowlands and wooded highlands. Prior to the eruption of the volcano an increasing number of earthquakes was felt each day for two weeks and more than 300 tremors occurred the day before it started.

Stories of its beginning are varied, but the most reliable is that the first event was a thin wisp of smoke which rose from the ground. In the course of three or four hours a hole was formed 30 feet deep and 10 feet in diameter, from which dense clouds of ash poured. The first explosion seemingly did not take place until about seven hours after the first smoke appeared. After the volcano started erupting on February 20, 1943, it exploded fairly regularly at intervals of four to six seconds for some ten weeks. Subsequently the rate of the explosions became somewhat irregular. In the first few weeks most of the material blown from the vent consisted of bombs. Ash formed a relatively minor part of the ejectamenta, but in April several periods of violent ash-emission occurred; and subsequent to that date the proportion of the material emitted in the form of ash was comparatively large.

The cinder-cone formed by the material thrown from the crater grew at a rapid rate. Within a week it was more than 500 feet high, and within ten weeks it was over 1,000 feet high. No lava flowed from the crater until early in June, some 15 weeks after the first explosion, though within two days lava appeared from a fissure some 1,000 feet north of the center of the cone, and in the course of seven weeks the lava advanced more than a mile. This lava flowed at a rate of three to ten feet an hour, and consisted of the aa-type. It subsequently developed fumaroles which gave off ammonium chloride principally. The lava contained phenocrysts of olivine and basic feldspar but was very viscous and light in color. The ground-mass seemingly was siliceous, as an analysis of a representative sample of the entire lava made by CHARLES MILTON [2] of the United States Geological Survey contained three per cent of quartz in the norm.

When I first visited Parícutin it was throwing bombs 2,000 to 3,000 feet in the air. Nearly all the bombs were solidified to such an extent that they were not deformed when they struck the earth. Most of them buried themselves three to four feet in the ground, leaving shallow holes in the soil where they came down. A few of the bombs consisted of a granitic rock that looked like diorite. The orifice from which the material was thrown seemingly restricted the ejection of the fragments because when I first saw the volcano, the bombs were blown out at an angle deviating 10° from the vertical, which caused the cone to be higher on the side toward which the bombs were thrown. In the course of six hours the angle of ejection gradually changed back to vertical and then to an angle deviating 5° from the vertical on the opposite of the cone.

When I visited the volcano in May, flashes of lightning 500 to 1,500 feet in length were observed in the ash-cloud above the cone, but none was seen when I visited it in February and in June.

On June 19, 1943, I flew over the volcano. At that time the cone was reported to be 1,200 feet high and lava filled the crater to within 50 or 100 feet of the top. The lava was frozen on the surface

and ash was issuing from a vent estimated to be 75 to 100 feet in diameter in the northwest part of the lava-field within the crater. On the east side, liquid lava was flowing from an opening in the side of the cone, 100 to 150 feet below the lip of the crater. This was eight days after the first lava had poured from the crater and four months after the first explosion. Since that date much lava has appeared, but details of the subsequent history are given in the paper by Dr. WHITE.

References

[1] PARKER D. TRASK, The Mexican volcano Parícutin, Science, v. 98, pp. 501-505, 1943.
[2] CHARLES MILTON, A preliminary report on the petrography of Parícutin lava-specimens, Trans. Amer. Geophys. Union, pp. 618-621, 1944.

U. S. Geological Survey,
Washington, D. C.

NOTES ON VOLCANIC ROCKS FROM PARÍCUTIN, MEXICO

Charles Milton

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United States Department of the Interior)

The small collection of lava-flows, bombs, and ashes from Parícutin, which are to be briefly described, was obtained from several sources and is far from being as completely representative of the volcanic history of the region as one might wish. Until, however, an adequate study is made, these specimens may serve to give some idea of the broader aspects of the local petrography. Each of the 17 specimens is numbered in the text, and in Table 1 is given the name of the collector and the place and date the rock was collected.

Three specimens of older, pre-historic, lavas from Parícutin, Toluca, and Popocatepetl may first be briefly described. The latter two are some hundred and fifty miles to the east of Parícutin. All three specimens, though essentially andesitic, differ markedly among themselves and from the contemporary Paricutin rocks.

The old Parícutin [see 1 of reference-number in Table 1] lava has diopsidic pyroxene as the mafic mineral; whereas the present-day rocks have olivine, the plagioclase is apparently more sodic, and a clear brown glass forms the ground-mass. Pyroxene, plagioclase, a little disseminated black iron oxide, and glass comprise the older Parícutin lava.

The Toluca lava [2], whose light color contrasts strongly with the dark gray of the other rocks, contains brown biotite and basaltic hornblende, neither of which is found at Parícutin.

Table 1--Source of specimens

No.	Collector	Location	Date
1	Carl Fries, Jr.	? Near Parícutin	
2	D. E. White	South shore of the crater lake in Nevado de Toluca	
3	D. E. White	North side of Popocatepetl, elevation 1300 feet	
4	G. A. Cooper (National Museum)	Flow of February 22, north-east side of volcano	?
5-7	D. E. White	East of volcano at 50, 8, and 4 km, respectively	March 25, 1943
8	Carl Fries, Jr. (lava)	Northeast flow of June	Mid-June, 1943
9	Carl Fries, Jr. (bomb)	Foot of cone	June 21, 1943
10	Carl Fries, Jr. (lava)	From northwest flow	Late July, 1943
11	Carl Fries, Jr.	From northwest flow	
12	D. E. White (lava)	July flow, northeast of cone	July 18, 1943
13	D. E. White (ash)	1-1/2 km, northeast of cone	July 18, 1943
14	D. E. White (lava)	Location not known	Date not known
15-17	D. E. White (bombs)	Foot of cone, north side	January, 1944

The Popocatepetl specimen [3] contains abundant phenocrysts of pyroxene, a mineral not seen in the contemporary Paricutin rocks, except possibly as exceedingly minute crystals in the groundmass.

The present Paricutin episode therefore has produced a different type of rock than these older eruptions. All, however, are doubtless related in the major regional orogeny.

Mention should be made of the extinct volcano Jorullo, situated some 40 miles east of Paricutin. In 1759 the volcano came into existence, with a history remarkably paralleling that of Paricutin. Analyses are recorded of the basaltic lavas, which are almost the same as those of the Paricutin rock. The several analyses of the Jorullo lavas, including one of a bomb, vary but little; this again parallels the constancy of composition noted in Paricutin. Petrographically, the published description of the Jorullo rocks could almost be that of the Paricutin rocks. The older eruption is the subject of an extensive paper by EZEQUIEL ORDONEZ [Guide des Excursions du 10th Congres Geologique International, Mexico City, 1906].

The oldest specimen at hand of the present volcanic eruption is from the flow beginning February 22, 1943 [4]. This is the only rock so far analyzed, but petrographically it so closely resembles the other Paricutin lavas that the analysis must fairly represent them all. The analysis and salient petrographic features are as follows:

SiO_2	55.04
Al_2O_3	18.82
Fe_2O_3	1.92
FeO	5.69
MgO	5.68
CaO	7.17
Na_2O	3.88
K_2O	0.85
H_2O	0.16
TiO_2	0.94
P_2O_5	0.21
S	0.04
MnO	0.07
BaO	0.06
Total	100.53

The norm computes to	
Quartz	3.06
Orthoclase	5.00
Albite	33.01
Anorthite	31.41
Diopside	2.69
Hypersthene	19.93
Magnetite	2.78
Ilmenite	1.82
Total	99.70

The rock is basaltic in habit but is to be classed as an andesite.

In section, the rock is highly porous, and in a glassy (?) base crowded with ore-grains are abundant uniformly-sized plagioclase laths, and a moderate number of fairly euhedral olivines. No quartz was seen. Miss JEWELL J. GLASS, of the United States Geological Survey, kindly checked the olivine--α1.675 γ 1.712, both $\pm$0.003 with 2V 88° $\pm$ 3° (about 80 per cent forsterite). The modal olivine, with normative quartz and pyroxene, indicates that the ground-mass may be quite siliceous.

It is indeed probable that the glassy (?) base contains very poorly developed pyroxene. However, even in a much more favorable section, where the probable pyroxene can be seen distinctly under very high magnification, it is still impossible to definitely identify the particles.

There are three specimens of ash-falls in March--one from 50-km [5] distance, the second about eight-km [6], the third four-km [7]. As to be expected, the greater the distance, the finer the ash--the most remote is like fine sand, the nearest, as coarse as gravel. The ash contains much olivine, and considerable uncrystallized dark opaque glassy material.

Two specimens date from June, one a lava [8], the other a bomb [9]. The flow specimen is very porous, with uniformly distributed openings. The lava between the pores is dense. The bomb-specimen is mostly dense and stony, but here and there is porous like the flow-rock. Both materials are reported to have had temperatures around 1,100°C when emerging from the volcano and were more solid than fluid. Under high magnification a thin section of the bomb shows very small prismatic crystals crowding the ground-mass with feldspar and ore-grains. These crystals have high relief, inclined extinction, up to about 40°, and fairly high double refraction. In all probability, they are diopsidic pyroxene. Another feature of interest is the presence of very sparing minute white grains in the black lava. These are quartz. It is believed, for reasons given later, that this quartz is not a product of crystallization of the andesitic magma, but is what remains of a foreign inclusion of quartz-bearing rock.

In the following month, July, were flows represented by a dense stony [10] lava, very much like the bomb-specimen just referred to, two porous lavas [11, 12], which again are practically identical with that from June, and an ash-fall [13], a specimen of which was taken only 1-1/2 km from the cone. Petrographically, there is little to differentiate the bombs and lavas; the ash-specimen, however, is distinctive. It is highly cellular, almost pumiceous, and consists essentially of a clear light-brown glass in which are strewn, not too abundantly, olivine and plagioclase. The olivine is remarkably embayed and corroded, as if it were dissolving in the magma prior to ejection of the ash. In the glass, besides these large corroded olivines and plagioclase, are numerous very small generally well-formed crystals that seem to be olivine too. It is possible that the magma which was dissolving the large olivine crystals reached, locally at any rate, a condition of equilibrium with respect to olivine, permitting it to crystallize in minute crystals even while elsewhere coarse olivine was dissolving. A similar phenomenon is often seen while watching the solution of a soluble salt, such as potassium iodide or cesium chloride, in water under the microscope.

A rather problematic specimen, picked up in the observatory, and probably dating from this time, is a sigmoidally folded sheet of lava [14], an inch or so thick. Apparently both top and bottom were exposed, and exhibit a thin chilled zone. Contraction on solidifying was considerable, as shown by criss-cross fractures, 1/8 inch deep, on top and bottom in the chilled zone. The highly porous pumiceous texture of the sheet is indicative of a considerable gas-content, which may have permitted the otherwise too viscous mass to flow.

The most recent specimens are three bombs [15, 16, 17], dating from January, 1944, which show some very interesting features. Unlike the preceding bombs, they consist of two quite distinct materials--one black lava, similar to other Paricutin lavas, the other a white rock, varying in texture from dense porcellanic to fragile clear glassy pumice. In thin section, this pumice is seen to consist of glass and, surprisingly, quartz. The quartz is in aggregates of shattered and strained grains, evidence of high temperatures; the glass is completely vitreous, without a trace of feldspar. A few turbid areas, however, are thought to have been originally feldspathic. The contact of glass and quartz is sharp, and the quartz shows rounded edges.

The quartz in the pumiceous material may lie only a fraction of a millimeter from olivine in the lava; it would seem that the glassy rock was able to melt until only some quartz-grains remained, without any appreciable degree of mixing of the two fluids. It may also be noted that whereas the glass of the andesitic lava is basaltic as shown by its high refractive index relative to Canada balsam, the glass of the pumice has a very low refractive index, and hence is much more siliceous, of a rhyolitic type. Fused albite would furnish a glass with refractive index under 1.50, whereas anorthite would fuse to a glass with index above 1.57.

NORMAN DAVIDSON, Chemist of the United States Geological Survey, kindly determined the silica in the pumice as 75.8 per cent. Considering that a considerable quantity of quartz is included, it is evident that the glass proper must contain much less SiO_2. In other words, it was not quartz that melted to produce the glass, save in a very minor degree, but rather the more fusible constituents of a rock in which quartz formed but a part. Certainly the white rock was not originally quartzite, as might perhaps be inferred on noting the association of quartz and glass.

The white porcellanic material in the bombs is definitely rhyolitic, possibly a rhyolitic breccia, as it is not uniform in appearance microscopically.

Occasionally rather vague plagioclase phenocrysts may be seen, but none of quartz. The contact with the andesite lava is very sharp, so far as the andesite is concerned; but the rhyolitic rock shows a peripheral zone of alteration, usually with better crystallization, against the andesite. It appears that the sequence of events is roughly: (a) An older rhyolite was invaded at some depth by the andesite; (b) fragments were dragged up in the rising lava-column; (c) during which time they were heated to incipient melting by the hot lava, the lava itself being unaffected by the inclusions; (d) later, with resurgence of volcanic activity, the slightly altered fragments were hurled out of the crater.

The outstanding impressions obtained from examination of these specimens are: (a) The very slight changes in composition of the lava during the year; (b) the simplicity of mineralogical composition, olivine, pyroxene (?), plagioclase, iron oxide, and glass, being the only substances seen; (c) the corollary lack of any evidence of contamination of the andesitic magma by absorption of material from the white inclusions in the bombs; (d) the higher degree of crystallization of the dense bombs and the lava in comparison with the ash.

Acknowledgments--The specimens described were collected by CARL FRIES, JR., and DONALD E. WHITE, who also supplied data relating to the specimens. Dr. C. S. ROSS and Dr. W. T. SCHALLER have made instructive suggestions in the presentation of these notes.

U. S. Geological Survey,
Washington, D. C.

PARÍCUTIN'S CYCLIC ACTIVITY

Donald E. White

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United States Department of the Interior)

Parícutin's volcanic activity during its first year of life included a number of periods characterized by flowing lava. The length of time of individual periods ranged from a few days up to more than a month, and were separated by intervals during which little or no lava flowed at the surface. A cyclic activity is therefore obvious, and a more or less permanent record remains in the form of the lava-flows. The complete cycle, however, is believed to consist essentially of four stages: (1) Flowing lava; (2) maximum gas activity from the central crater (without flow); (3) the rise of lava in the vent; (4) breaching of the cone in preparation for renewed flow.

The author has played only a minor part in the investigations that are being continued at Parícutin under the able direction of Dr. EZEQUIEL ORDOÑEZ and Dr. WILLIAM FOSHAG. These two men have spent many months at the volcano, and each is much more familiar with its phases of activity than are any other geologists. The many stimulating conversations with them are gratefully acknowledged. Neither one is to be held responsible, however, for the theoretical interpretations that are presented in this paper. The information on the early activity was given generously by Dr. ORDOÑEZ, and that of the lava-flows of June, 1943, by Dr. FOSHAG. The author regrets that circumstances have prevented their reading and criticizing of this paper before its publication.

The author is particularly grateful to Dr. E. G. ZIES of the Geophysical Laboratory of the Carnegie Institution of Washington for his very generous help and great interest in the problem, his stimulating influence, and his critical reading of the manuscript. He first pointed out to the author one of the three essential principles that are believed to control the cyclic activity.

A. F. BUDDINGTON, C. S. ROSS, and other associates of the United States Geological Survey have been very helpful in many ways.

The author has spent a total of only 12 days at the volcano during the first year of its activity. Table 1 shows a comparison of the activity of the gas-charged column with that of the lava during these days. This Table indicates that the evolution of gas through the central crater is generally relatively weak shortly before and during the flow of lava, and is generally strong at other times. Lag-effects, however, are very pronounced. A graphical correlation of the two types of activity is shown in Figure 1.

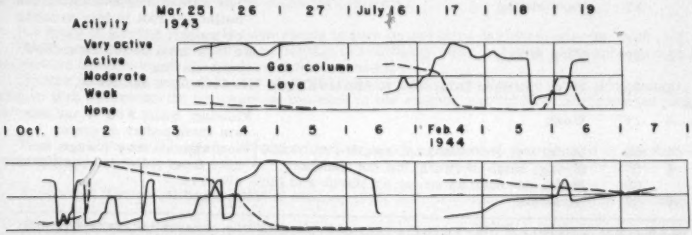

Fig. 1--Graphical correlation of the two types of activity at Parícutin

Table 1--Comparison of gas-column with lava-activity

Date	Hour[a]	Relative activity of gas-charged column	Lava-activity
1943			
Mar. 25-27	All	Very strong; abundant ash and bombs	Front almost dead; no new lava from outlet (concealed?)
Jul. 16	Noon	Weak; individual explosions	Lava flowing (N 30°E outlet; S 50°W outlet active?)
17	06:30	Strong; continuous, roaring emission	No new lava; at 10^h, SW side still slightly active
	Noon	Very strong; abundant ash and bombs	No activity
18	08	Strong; less ash than before	No activity
	15	Weak, abruptly; quiet, few minor explosions	No activity (Total time of lag, 11 hours)
	15:30	Weak; absolutely quiet	No activity
	16	Weak; some explosions, growing louder	No activity
	21	Weak; strong explosions; lava-pool forming?	Crater sagging above outlet; lava moving in vent
19	02	Weak; strong explosions; lava-pool formed?	Lava flows from outlet; crater sags much more
	05	Strong, gradually; no pronounced explosions	Lava stops flowing; completely stopped by 10^h
Oct. 1	13	Strong	Probably no lava; next day's flow a new surge
	18	Weak, rather abruptly; quiet, no explosions	Probably no lava; outlet on SW side, opposite observatory
	21:30	Weak; explosions start; lava-pool forming?	Probably no lava; outlet S 30°W of cone
	23	Strong; changes gradually	Probably no lava
2	04	Weak; quiet, no explosions	Flowing; exact time of new surge not known
	10	Weak; some explosions	Flowing; lava-fountain 50 feet above outlet; flow 8 feet per second
	Noon	Moderate; a few bombs fell outside crater	Flowing; flow less rapid, no fountain, but surges
	15	Weak; minor explosions, mostly is quiet	Flowing
	24	Strong; bombs abundant	Flowing? Not observed, but probably some flow
3	04	Weak; minor explosions, mostly is quiet	Flowing? Not observed; rate may be increasing
	19	Moderate; in afternoon, two gas-columns	Flowing; at 10^h, rate of flow three feet per second
4	01	Strong; changes gradually	Flowing; rate of flow undoubtedly decreasing
	04	Weak	Flowing
	08	Strong	Flowing; rate of flow decreasing
	17	Very strong	Flow almost stopped; rate from outlet one foot in four seconds or more
5	17	Very strong	No lava from outlet; flow-front still moving
6	10	Weak (as seen from road to Mexico City)	No lava from outlet?
1944			
Feb. 4	11	Weak	Flowing; outlet S 60°W and one km from center of crater
5	08	Moderate; continuous column, but no bombs	Flowing; rate may change, but rate from outlet impossible to observe
6	04	Strong; bomb-showers, but not abundant	
	08	Moderate; none as strong as March and July	
7	09	Moderate	Flowing?

[a] Each observation continues in time up to the hour of the succeeding observation, except at end of each trip.

The terms such as weak, moderate, etc., that are used to describe the degree of activity are of course comparative and cannot be defined in an exact, quantitative way. The author's use, without going into extensive detail, can be pictured by describing only two of the terms. As applied to the flowing lava, "active" indicates the extrusion of liquid lava comparable to a flow in a channel about 25 feet wide moving down a 20° slope at a rate near the outlet of about one to three feet per second. The same term applied to the gas-charged column is used to indicate a dark-gray continuous, violent column filling nearly all of the crater, and forced upward with an average speed in the order of several hundred feet per second, and rising almost vertically to a height of at least 5,000 feet. There are individual surges, throwing large amounts of ash and bombs into the air. The bombs are commonly thrown to a height of more than 1,000 feet above the lip of the crater, and most of them fall on the outward-dipping slopes of the cone.

"Weak," as applied to the lava, represents a slight movement of almost solid material from the outlet. The surface of the flow is completely solidified but some incandescent lava can be seen in the deeper cracks that break the surface. The same term as applied to the gas-charged column represents a thin, tenuous white or light-gray column drifting slowly upward, filling only a small part of the crater, and carrying little or no ash. The individual explosions may sound much louder than during the periods of greater activity, but average quantity of gas evolved is much less. Most of the bombs rise no more than a few hundred feet above the lip of the crater, and rarely fall on the outer slope of the cone.

Figure 2 illustrates the author's conception of the mechanism of the cyclic activity. The following is a brief summary of the pertinent points of each diagram.

(A) Stage of rising lava--The lava rises toward the surface due to one or more of these factors: (1) Expansion of the lava in the magma-chamber due to vesiculation, which in turn is due to the increased vapor-pressure caused by the crystallization of the lava [see 1, 2, 3 of "References" at end of paper]; (2) orogenic pressure on the walls of the magma-chamber [4]; (3) difference in density between the liquid lava and the solidified walls of the vent [5]; (4) gas-fluxing and/or assimilation of the overlying wall-rock [6]; and (5) stopping of the overlying rock [7].

Each of the first three factors, if it is dominant, must exert sufficient upward pressure to overcome the strength of the overlying rock. The tremendous energy of the gas-charged column is obvious to any observer, and leaves no doubt in his mind that the first of these factors is certainly important near the surface, regardless of the forces that originally caused the lava to start rising.

This stage (A) prevailed up to February 20, 1943, and was indicated by increasing earthquakes and underground noises.

(B) Stage of explosive activity--(1) The volcanic products first reach the surface.
(2) A small cone is built by the ejectamenta.
(3) The pressure on the lava-column is lowered by an amount equal to the pressure that was necessary to overcome the rock-strength during stage (A).
(4) The decrease in pressure on the lava-column results in an increase in vesiculation [8, 9].

This stage of cone-building lasted for two days. The first activity at the surface was probably due to gases that had advanced ahead of the lava-column.

(C) Stage of flowing lava--(1) Lava starts to flow on the third day, February 22, 1943 [10].
(2) The activity of the gas-charged column is relatively weak, but with loud explosions as the gas-bubbles break through the surface of the viscous lava.
(3) The increased vesiculation of stage (B) lowers the average density of the lava-column, which in turn decreases the pressure on the base of the column, and further increases the rate of vesiculation.

This is a "snowball"-effect, always with a lag in the response of vesiculation to the decrease in pressure.

This stage lasted until the middle of March, 1943, followed by cyclic gradations into stage (D).

(D) Stage of maximum gas-activity from the central crater--(1) This stage is reached when the gas-bubbles become so abundant that they can carry out the overlying lava instead of passing up through it.

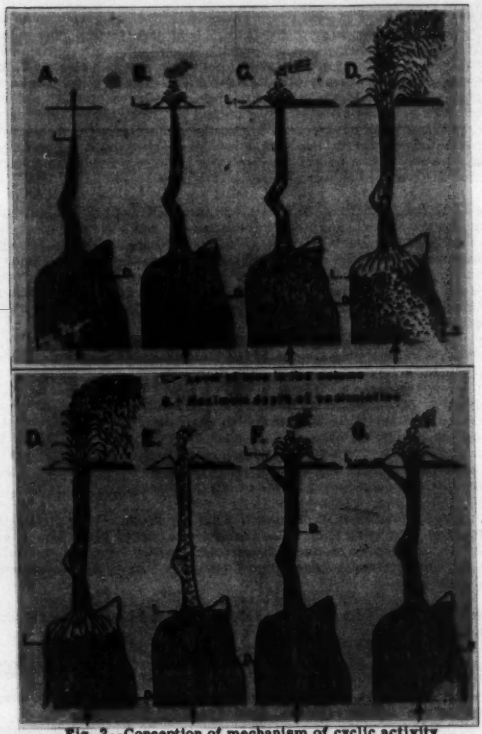

Fig. 2--Conception of mechanism of cyclic activity at Parícutin

(2) The average density of the lava-column has decreased while the upward strain of the bubbles has increased.

(3) Explosive "blowing" results. It consists of a continuous, violent gas-charged column, with a tremendous amount of ash and bombs, although the quantity varies greatly. There are individual upward surges, but the noise of the explosions is not very pronounced above the general noise, and never as loud as the explosions of stages (B) and (C).

(4) The flow of lava stops at or soon after the beginning of the stage.

(5) The vent is widened. Many of the bombs are dense and not very vesicular. They were probably torn from the walls of the vent.

This stage apparently lasted from late March to early June, 1943, almost without interruption, and with little or no lava flowing at the surface. The total rate of ejection of liquid and solid material may equal the rate of lava-emission during stage (C), but the amount of gas greatly exceeds that of stage (C). This relative separation of gas from liquid and solid material is the reason why a "collecting" chamber at depth is suggested. This may be only a local widening of the lava-vent, and may not be the main magma-chamber. A separation or "boiling" effect probably could not continue with such violence, over such a long period of time, in a narrow tube without a "bogging down" or exhaustion of the process.

(E) Stage of the silent rise of the lava in the vent--(1) The relative loss of volatiles during stage (D) decreases the vapor-pressure in the lava and, of greater importance, the loss of volatiles raises the melting-point of the lava, causing crystallization [10].
(2) Both of these factors increase the viscosity of the remaining liquid.
(3) The rise is caused by the relatively constant inflow of lava from below into the "collecting" chamber. This influx has been evident during all of the stages.

This stage is introduced rather abruptly without much gradation. The volcano is almost completely quiet for several hours or more. In the future, this stage may lengthen as the activity dies, to become a stage of repose before lava again rises.

(F) Stage of the breaching of the cone in preparation for renewed flow--(1) The bubbles that remain below are reabsorbed due to the increase in pressure. The somewhat higher gas-content of the lava lowers its melting-point slightly [11]. Such a mechanism may explain the rounded absorption-borders of the phenocrysts and, in other localities, the oscillatory zoning of feldspar phenocrysts. The feldspar phenocrysts of this lava are small and lath-shaped, but a few have been found that show oscillatory zoning.
(2) A lava-outlet starts to form when the hydrostatic pressure of the lava in the upper part of the column exceeds the strength of the walls of the vent.
(3) This stage may continue for several days.

Explosions are most noticeable during this stage. The difference is believed to be more apparent than real, with the observer more aware of the explosions and the apparently greater noise because it comes from a source near the top of the crater, instead of being muffled down in the vent, as it is during stages (E) and (G).

The evidence that the lava actually is high in the crater during this stage is supported by two observations. The trajectories of all of the individual bombs from a single burst are at times flat and low, and when projected back to a single point, this point is found to be not far below the top of the crater. At one time during this stage, low clouds drifted over the crater. The clouds showed a light-and-shadow effect caused by incandescence within the crater at a time when there were no explosions. The incandescence must have been very pronounced, from a source relatively near the clouds--that is, high in the crater.

(G) Stage of flowing lava--(1) Lava breaks out from a vent near the base of the cone. (No lava has flowed out over the lip of the main crater.)
(2) The lava that first flows out is "exhausted" lava, relatively low in volatile content.
(3) This lava is gradually replaced by lava from below the "collecting" chamber, with all or most of its original volatile content.
(4) Because of this, the rate of vesiculation gradually increases. This stage marks the end of a cycle and the beginning of another, starting again with a stage similar to (D).

The author is fully aware that only 12 days of observation during four trips spaced over a year is too short a time for a complete proof of his hypothesis of the relation between the lava-flows and the activity of the gas-column. However, Table 1 indicates that, at least for these days, a relationship is apparent. The proposed hypothesis appears to be the best explanation for the phenomena seen by the author, and for most of the relationships that have been described to him by others. A number of circumstances can conceal or obscure what is believed to be the basic relationships just described. Among these are:

(1) The very important lag-effects of the lava-activity, delaying its expected response from a few hours to several days or more (see Fig. 1 for July 18-19 and October 4). This lag is due to its very high viscosity, and to the necessity for the accumulation of lava to build up a hydrostatic pressure great enough at the base of the crater to overcome the strength of the cone and to start a new flow.
(2) This lag-effect means that the activity of the lava does not respond to short-time changes in the activity of the gas-charged column (see Fig. 1). Thus, if lava is flowing, and the column changes from weak to strong, and within a few hours back to weak again, little or no change is to be expected in the activity of the lava-flow.
(3) During stages (F) and (G), the main crater may be a compound crater with two or more gas-vents, each with a more or less distinct gas-charged column. A new stage (D) may start in one column before it enlarges sufficiently to absorb an adjacent column that may be supplying the lava-flow. This may delay the end of a lava-flow and obscure the relation of the activities.
(4) During many flows, the lava-outlet could not be closely observed. Cone-material was commonly dragged out on the surface of the flowing lava. At other times lava welled up near the

center of a field of hot flow material, and the changes in the rate of emission could not be observed accurately. It should be pointed out that detailed, hour-by-hour correlations of the two types of activity are necessary.

(5) Observations on the front of an extensive lava-flow show much less correlation with the activity of the gas-column than do those made at the lava-outlet. The front of a large flow has continued to move for days after lava ceased flowing from the outlet. Unfortunately, observations on the rate of movement of the front of the flow are the only ones that can be made accurately in a quantitative way.

(6) Fortuitous circumstances such as internal avalanches and the breakdown of the over-steepened internal walls of the crater and the vent during stage (E) may delay or obscure the cycle. During stage (G) the "exhausted", almost completely crystallized, lava readily congeals on the walls of the vent, restricting or closing it, delaying the next stage, and favoring the formation of two or more gas-vents during the next stage.

(7) The rate of inflow of the lava into the "collecting" chamber from below is assumed to be constant during a single, complete cycle of activity. Actually the rate of inflow probably varies greatly, hastening or slowing down the normal succession of the stages of activity. This may be indicated by the short-time cycles, at times incompleted, that occur within the major cycles.

(8) Other unknown factors are probably influential in determining some of the minor effects.

The proposed mechanism may explain the activities of some other volcanoes that are characterized by strong explosive activities and flowing lava. PERRET [12] has ably described in vivid detail the various phases of the activity that make up the Vesuvian cycle. The different phases can be regrouped, but with the same relative order in time, into four stages of activity that are almost directly comparable in characteristics and succession to the Parícutin cycle as it is recognized by the author. It should be pointed out that the Parícutin cycle was derived independently, without reference to PERRET'S descriptions. The Vesuvian cycle, with the author's breakdown of the successive phases into stages, is:

(I) The tremendous explosive eruption of 1872 [13]--comparable to stage (D).

(II) Stage of repose for three years after the eruption, until 1875 [13]--comparable to stage (E).

(III) Stage of crater-filling, from 1875 to 1881, without any external laval flows [13]. The bottom of the crater was built up, and the lava-column rose by means of small internal flows on the crater-floor, and the growth of small internal cones--comparable to stage (F).

(IV) Stage of external flows, from 1881 to April 7, 1906 [14]--PERRET'S personal observations started in 1903. During this time at least six major flows were extruded. Each one of these may mark a minor cycle or an incompleted cycle within the major cycle, just as the activities at Parícutin during July 18 and 19 (see Fig. 1) constitute a minor cycle within the major cycle. At Vesuvius during this stage, the internal cone was gradually built up above the enlarged crater of 1872, and the explosive activity increased. The first lava-flows were apparently lower in gas-content than the later flows, according to PERRET. This is in accord with the demands of the present theory. The main difference between PERRET'S stages of activity and those of the author is that PERRET includes the last major flows of (IV) in a group comparable to (V), and the gas-activity of the latter group is subdivided into three parts--comparable to stage (G). The cycle is completed.

(V) Stage of maximum gas-activity, from April 8-22, 1906 [15]. PERRET believed that this stage was brought about by the very high stand of lava in the column, followed by the rapid lowering of lava in the column due to its flow from outlets at very low altitudes on the sides of the cone. The sudden release of pressure allowed the contained gases to "flash" into eruption. This factor of a lowering of the lava in the vent is believed to be present at Parícutin, but is probably of less importance because of the apparently higher viscosity of Parícutin's lava, due at least in part to its higher silica content [16, 17]. At Vesuvius the replacement of "exhausted" lava by lava with a normal gas-content through the long succession of flows may be very important--comparable to stages (I) and (D), except that the presence of a "collecting" chamber at Vesuvius is not indicated as clearly as at Parícutin.

(VI) Stage of repose, from 1906 to 1913 [18] when internal avalanches modified the over-steepened inner walls of the crater and the vent. During this stage the lava-column rose slowly up the vent and through the avalanche material, appearing in the bottom of the crater in July, 1913--comparable to stages (II) and (E).

(VII) Stage of crater-filling, from 1913 until the end of PERRET'S observations in 1922 [19]--comparable to stages (III) and (F).

The author believes that the mechanism outlined in stages (D) to (G) of the Parícutin cycle may, therefore, apply directly to the comparable stages of Vesuvius, with the modifications or exceptions that have been mentioned. The Vesuvius cycle is generally completed in about 30 years, according to PERRET [20], whereas the major Parícutin cycles were repeated about every one to three months during the first year of its activity.

The proposed mechanism, if it actually operates, requires that all or most of the following relationships are to be expected and should be looked for at Parícutin to prove or disprove the proposed hypothesis. The author regrets that he is unable to make these investigations at the present time.

(1) The first ash in a major ash-stage (D) should be less crystallized than the ash from the last part of the stage.

(2) The cinders in the succeeding stage of flowing lava [stage (G)] should show the reverse trend, from relatively well crystallized to less crystallized. Almost no ash, and only a very few cinders are thrown out during this stage, but some can be collected. The degree of crystallization of the cinders throughout the stage should be much higher than that of the ash and cinders of stage (D), which is only 30 to 40 per cent crystallized.

(3) The bombs thrown out of the crater during stage (F) should contain larger, and possibly more vesicles than the dense bombs of stage (D) that are believed to come from the walls of the vent.

(4) A larger proportion of the bombs of stage (F) may be more liquid when thrown out, and should have a larger proportion of glass in the ground-mass than the very dense bombs of stage (D). Actually, two types of bombs should be found during stage (F). One should be the solidified crust that has formed at the surface of the lava "pool," and the other a somewhat liquid type with a fairly high degree of crystallization, formed directly from fresh lava rising to the surface of the "pool," and thrown out immediately. The material coming directly up from the collecting chamber during stage (D) would form the most glassy and vesicular of all the bombs except that none of it probably persists in a massive form, but is broken down into ash and cinders by the violently escaping gases.

(5) The relative abundance of dense bombs and of bombs of foreign material should be much greater during stage (D) than during stages (F) and (G).

(6) The first surge of lava after a long period of maximum gas-activity should be lower in gas-content, more crystallized and less vesicular, and may contain more blocky inclusions than the lava extruded at the end of a period of flow. This entails a difficult problem in collecting representative samples. The front of a new major flow can be sampled readily at a point near the outlet, but generally it would be very difficult to obtain a sample near the outlet at the end of a major period of flow. At times, however, a new outlet is formed late in stage (G), or a flow breaks out of its old channel near the outlet. Under these circumstances, significant collections could be made.

(7) The first lava appearing in a new period of flow should show less resorption of the olivine phenocrysts, and less oscillatory zoning of the feldspars than the lava appearing several days later. The lava at the very end of a period should probably show the least of these phenomena. [See comments for stage (F).]

(8) The first lava-flow in February and March, 1943, may have had a higher gas-content than the succeeding lavas because it did not follow a prolonged stage similar to (D). On the other hand, however, the slow upward migration and crystallization may have allowed the gases to escape upward and outward into the wall-rock. This may explain the absence of a prolonged stage similar to (D), following directly after stage (A).

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Washington, D. C.

PARÍCUTIN MAGNETIC SURVEY

Ralph R. Bodle

This survey was a joint project of the United States Department of State and the United States Coast and Geodetic Survey. The purpose was to learn whether any detectable change had occurred in the Earth's magnetic field in the region as a result of the volcano. Work started the latter part of May and continued well into July, 1943. The Mexican Government cooperated enthusiastically, giving assistance in every possible way.

The background for the project was somewhat limited as little work of this type had ever been done. It was unique as an opportunity to observe under actual eruption conditions.

The Japanese are known to have made observations around several of their volcanoes and claim to have found anomaly changes with time as a result of repeat surveys.

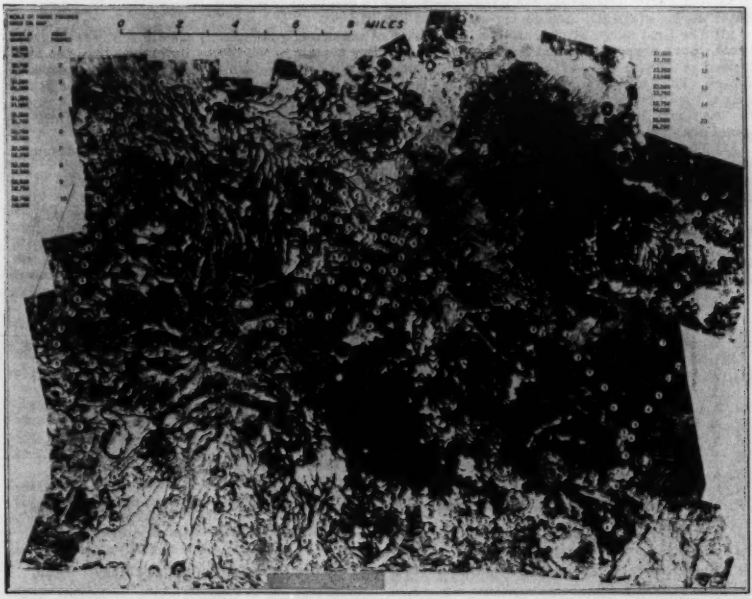

Fig. 1--Mosaic airphoto of region near Parícutin Volcano, Michoacan State, Mexico (original by courtesy of Compañia Mexicana Aerofoto, S. A., Calle 123, No. 86, Mexico, D. F., reduced approximately 18 to 1)

Work done by the Carnegie Institution of Washington in the vicinity of Santa María Volcano in Guatemala was reported in the Transactions of the American Geophysical Union for 1941 [pp. 508-512. Large anomalies in the Earth's magnetic vertical intensity were found, and it was expected that similar conditions might be encountered around Paricutin.

Magnetic anomalies are difficult to deal with in the construction of magnetic maps, and since the United States Coast and Geodetic Survey makes such maps for use of sea and air navigators, it could not well neglect the opportunity to observe a possible magnetic anomaly in the making. It would have been very valuable if a survey could have been made before the volcano appeared. The next best thing was to observe during the eruption.

ALFONSO DE LA O. CARREÑO, a Mexican engineer, advocated a magnetic survey in a list of six recommendations made in March, 1943. Only one practicable way was found to accomplish the work. This was for the United States Coast and Geodetic Survey to do it as a supplementary project in a program of magnetic repeat-surveys being carried on in the American Republics. The possible extent of the survey of Paricutin was fixed by time-factors including the need for finishing before the rainy season began.

Previous surveys of similar character by the United States Coast and Geodetic Survey were few, but the Survey was greatly aided in planning the work by the cooperation of members of the Carnegie Institution of Washington who had taken part in the survey of Santa María Volcano. It was agreed that no attempt should be made to apply the corrections which are made in an area of slight anomalies.

The writer, accompanied by NELSON C. STEENLAND of the Survey, who made most of the magnetic observations, and by A. G. CALDERON, who was assigned by the representative of the

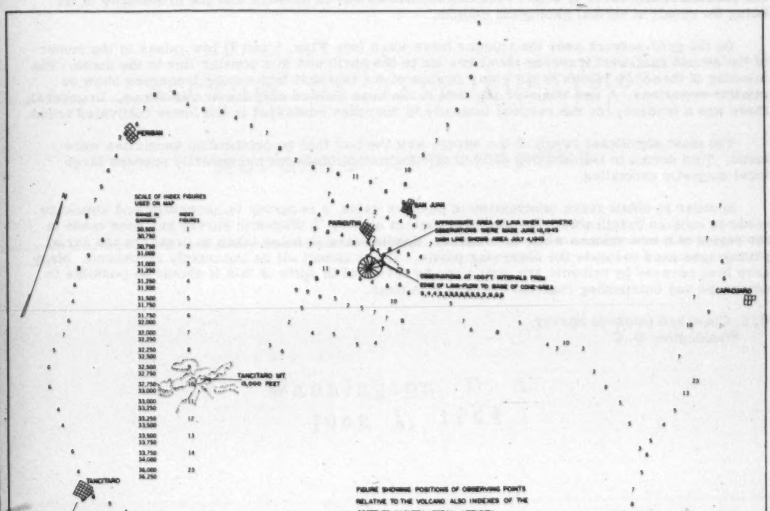
SCALE OF INDEX FIGURES USED ON MAP
RANGE IN GAMMAS
INDEX FIGURES
30,500 - 30,750 1
30,750 - 31,000 2
31,000 - 31,250 3
31,250 - 31,500 4
31,500 - 31,750 5
31,750 - 32,000 6
32,000 - 32,250 7
32,250 - 32,500 8
32,500 - 32,750 9
32,750 - 33,000 10
33,000 - 33,250 11
33,250 - 33,500 12
33,500 - 33,750 13
33,750 - 34,000 14
34,000 - 34,250 23
PARICUTIN
SAN JUAN
APPROXIMATE AREA OF LAVA WHEN MAGNETIC OBSERVATIONS WERE MADE JUNE 10, 1943
DASH LINE SHOWS AREA JULY 4, 1943
OBSERVATIONS AT 100 FT INTERVALS FROM BASE OF LAVA-FLOW TO BASE OF CONE-AREA
9,9,9,9,9,9,9,9,9,9,9,9,9,9,9,9
CARAPUNO
TANCITARO MT.
13,000 FEET
TANCITARO
FIGURE SHOWING POSITIONS OF OBSERVING POINTS RELATIVE TO THE VOLCANO AND INDICES OF THE OBSERVED MAGNETIC VERTICAL INTENSITY
URUAPAN
INDEX-FIGURES FOR THE LINE TANCITARO TO APATZINGAN ARE 6,5,5,5,5,5,6,7,7,7,5,5,5 7,6,7,6,5,5,5,6. OBSERVATIONS WERE TAKEN AT APPROXIMATELY ONE KM INTERVALS

Fig. 2--Sketch showing positions of observing points relative to the volcano; also indices of the observed magnetic vertical intensity

Mexican Government to assist in the work, arrived at Uruapan May 17, 1943, with a truck and equipment. On May 18 they made their first trip to the volcano to obtain a better idea as to what sort of problems they were facing.

It was obviously impractical to mark the observing points. Dr. PEDRO C. SANCHEZ, Director of the Pan-American Institute of Geography and History, had given the party some aerial photographs of the immediate vicinity. It was decided that these might serve the needs for plotting the observing points with reference to the volcano. The photographs will probably be the most practical means for making a resurvey.

Lines were run to form a grid in the immediate vicinity of the volcano. Observations were spaced about one km apart on the traverses, while the parallel lines averaged about 1-1/2 km apart. Having finished this region, the observers felt the survey should be extended. Through assistance of Dr. SANCHEZ and Federal Government officials in Mexico City, they were able to obtain an air mosaic covering some 1,140 square kilometers (400 square miles). A line of observations was then run around the outer edge of this area except for a short distance in the northeast portion. A short line was run from the outer edge of the lava-flow to the edge of the cone. Next, it appeared desirable to carry a line out onto the flood-plain to the south (Tancitaro to Apatzingan). This was accomplished with some difficulty. It was now felt that sufficient observations had been made to determine whether the volcano had made any detectable regional changes in the Earth's magnetic field. By this time the observers had also formed tentative opinions as to what significance could be attached to the results.

One area of strong anomaly was found a short distance north of Periban but was very local in nature as it was at a point where the survey-line crossed a clearly perceptible dyke or outcrop. One of the highest values observed was a short distance north of Uruapan, but it was felt that this did not reflect any effect of active volcanic conditions due to distance and the probability of its being the result of normal geological causes.

On the grid-network near the volcano there were (see Figs. 1 and 2) low values in the center of the second east-west traverse about two km to the north and in a similar line to the south. The meaning of these low values is not clear in view of the fact that intervening traverses show no similar variations. A line run over the lava to the cone showed only minor variations. In general, there was a tendency for the vertical intensity to decrease somewhat in the lower cultivated areas.

The most significant result of the survey was the fact that no outstanding anomalies were found. This seems to indicate that all volcanic formations may not necessarily possess large local magnetic anomalies.

In order to obtain more information of positive value, a resurvey is necessary and should be made as soon as practicable. For the first time in history, a magnetic survey has been made in the region of a new volcano while in eruption. Special care is being taken to preserve the aerial photographs used to locate the observing points. These cannot all be accurately recovered. Many have been covered by volcanic ash, and some by lava, but in spite of this it should be possible to determine any outstanding regional changes with time.

U. S. Coast and Geodetic Survey,
Washington, D. C.

AMERICAN GEOPHYSICAL UNION

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THE MECHANICS OF THE LITHOSPHERE AND ITS RELATION TO GRAVITY ANOMALIES AND FRACTURE

Ross Gunn

The lithosphere may be defined as the cool, strong, rocky layer of the Earth that is supported by the denser, weaker, and relatively hotter underlying magma. The upper few kilometers of the lithosphere are traversed by many faults and fractures, but below this surface level it is sufficiently homogeneous to support great superimposed geological loads.

Three fundamental assumptions may be made concerning the lithosphere. It may be assumed to be (a) perfectly rigid, (b) plastic, or (c) elastic. The mechanical implications of the first two assumptions are readily formulated in quantitative terms and have been widely employed in the calculation of the BOUGUER and the isostatic anomalies. The mechanics of the elastic lithosphere is somewhat more complicated but it is possible to work out quantitatively its deformation under certain types of loading that closely approximate many actual geological features. Comparisons of the important consequences of the three basic assumptions enumerated above may be made, and these are given in Table 1. An analysis of the deformations of the elastic lithosphere leads at once to the principle of isobaric equilibrium and this principle embraces both the Bouguer and isostatic types as special cases. For example, it may be noted from the Table that when $y = 0$ the principal term of the isobaric gravity anomaly correctly reduces to that given for the Bouguer anomaly. Further, when $hd = yd_0$ the isobaric anomaly is zero, corresponding to the isostatic case. It may be recalled that the relation $hd = yd_0$ expresses the condition for hydrostatic equilibrium and, therefore, is always identified with isostatic equilibrium.

Table 1--Comparison of various types of lithospheric equilibrium

Assumed character of lithosphere	Sufficient approximation for actual Earth when load is	Resulting character of equilibrium	Lithospheric constant	Type of anomaly	Principal term of gravity anomaly
Rigid	Small and concentrated	Mechanical	Zero	Bouguer	$2\pi\gamma dh$
Plastic	Uniform and larger than 330 km	Hydrostatic	Infinite	Isostatic	Zero
Elastic	Unrestricted	Mechanical and hydrostatic	$8.4 \times 10^{-8} cm^{-1}$ (Gunn)	Isobaric	$2\pi\gamma(dh-d_0y)$

In above equations, h is the height of an impressed block-load having a density d, y is the downward deformation of the neutral axis of the lithosphere, d_0 is the density of the underlying magma, and γ is the gravitational constant.

In evaluating the downward deformation, y, of an elastic lithosphere, due to a superimposed load, it is necessary to determine not only the restoring force provided by the underlying displaced magma, but also the internal forces that arise from the deformation of the lithosphere itself. These internal forces produce a resultant vertical stress that contributes to the support of the impressed load and thus require a modification of the contemporary ideas associated with isostasy. The author has shown in a series of papers appearing in the Journal of the Franklin Institute [see 1 of "References" at end of paper] that the isobaric equilibrium of the lithosphere is specified by the relation

$$Mg + S_v = \text{a constant} \qquad (1)$$

where M is the mass within a prism of unit-area above some selected gravitational equipotential surface, g is acceleration due to gravity, and S_v is the vertically downward stress applied to the prism as a result of the deformation of the lithosphere. This isobaric expression differs from the equivalent expression describing isostasy by inclusion of the added term involving the vertical stress.

The evaluation of the downward deformation y, due to any arbitrary superimposed load is usually awkward and laborious, but solutions are found relatively easy if the load happens to be approximately linear and extends more than 1000 km. Such a long linear load may be a long mountain chain, a chain of volcanic islands, or a load of sediments deposited along a continental border. A typical section of the lithosphere of unit-width extending at right-angles to the axis of the assumed linear earth-feature is adopted for study. Such a section of the lithosphere extending down to the weak magma is equivalent to a beam carrying the assumed load. In an earlier paper on mountain building, the deformation of such an equivalent unbroken beam, supported by a weak magma, was worked out for a single force. It was shown therein that the downward deformation y at any point x, measured along the axis of the beam and due to a force F applied at the origin is

$$y = [(b/2)\, F\epsilon^{-bx}/d_0 g]\, (\cos bx + \sin bx) \qquad (2)$$

where b is a fundamental constant of the lithosphere that may be either calculated or determined by observation. This expression may be employed to determine the downward deformation for any arbitrary long linear load provided one notices that the force F in equation (2) can be replaced by the elementary load (hdgdx) if y is replaced by dy, whence one may write

$$dy = (bH/2)\, \epsilon^{-bx}\, (\cos bx + \sin bx)\, dx \qquad (3)$$

where H is defined as the height which the applied load would have were it of the same density as the underlying supporting magma. This equation may be integrated to determine the deflection of the lithosphere at any selected point. It has been shown in the referenced papers that the following equations describe the various important quantities to be evaluated.

$$H - y = (EI/d_0 g)\, (d^4 y/dx^4) = \Delta g/2\pi\gamma d_0 = -(S_v/d_0 g) \qquad (4)$$

where I is the sectional moment of inertia per unit-width of the equivalent beam, and E is the equivalent elastic modulus.

By solving the differential equation of (4) through the use of equation (3), it is usually possible to determine the figure of the deformed lithosphere. That is to say, y can be expressed analytically as a function of the distance x along the beam.

With a knowledge of the deformed figure of the lithosphere and the relations expressed by equation (4), the principal term of the gravity anomaly Δg can be evaluated as a function of its position. Hence, for the first time, it is possible to forecast finite gravity anomalies in deformed regions of the Earth's crust. Further, because the figure of the lithosphere is known, it is possible to evaluate its curvature and hence, according to the fundamental laws of elastic beams, one may evaluate the distributions of fiber-stress in the lithosphere as it is deformed. It should be clear, therefore, that if the load applied to the lithosphere can be evaluated and if the lithospheric constant b is known, then the stress anywhere in the lithosphere may be computed. As an example illustrating the utility of the investigation, the author has determined the approximate figure of the lithosphere in the region of the Hawaiian Islands and from its values has estimated the gravitational anomalies in the region, as well as the distribution of the fiber-stress. In a similar way, an analysis has been made of the Atlantic Coast regions in which it has been found possible to forecast with some success the distribution of gravity anomalies and the position where crustal failure will be produced by the applied load. It is found from the calculations that the load applied along the Atlantic Coast has the right magnitude and distribution to produce the observed failure of the crust along the well-known Atlantic Coast Fall Line.

This communication is a very brief review of the author's referenced works on the subject-matter which show that a strong elastic lithosphere characterized by the constant $b = 8.4 \pm 2 \times 10^{-8} cm^{-1}$ has a real and important geological existence.

References

[1] ROSS GUNN, J. Franklin Inst., v. 224, p. 19, 1937; v. 236, p. 47 and p. 373, 1943; v. 237, p. 139, 1944.

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WHY PETROFABRICS?

Earl Ingerson

Introduction

The question "Why petrofabrics?" has been asked innumerable times in one form or another in recent years by professional geologists as well as by students. The following has been prepared in an attempt to answer this question by outlining:

(1) What petrofabrics includes; how it is like structural geology and how different from it;
(2) Typical problems in various fields of geology to which petrofabric methods have been applied successfully;
(3) Other problems in which petrofabrics should prove helpful; and
(4) Some of the things needed to place petrofabric interpretations on a more secure basis.

No attempt is made to discuss theories of deformation, details of petrofabric techniques, or the meaning of symmetry of diagrams. Definitions of terms are not even given. The paper merely points out what petrofabrics is, cites typical examples of what it has done, and suggests some things it can do.

Petrofabrics defined

What is petrofabrics? In the chapter on Structural petrology in his new text-book of Structural geology, BILLINGS [see 1 of "References" at end of paper] defines petrofabric analysis as the "study of the internal structure of rocks and its relation to the movements involved in their formation or deformation." From the discussion that follows it is clear that he is thinking of fabric chiefly in terms of mineral arrangement. This is only one element of fabric in its larger sense, grain-fabric But the word as it should be understood in petrofabrics is much more comprehensive. In this sense it is analogous to the fabric of a building, that is, its entire make-up from the structure of the individual bricks and the mortar that holds them together, to the steel framework that binds the whole into a unit. In other words, fabric includes all of the spatial relations of a rock from the space-lattice of the individual mineral grains through cleavage, fractures, joints, schistosity, lineation, and fold-axes. Therefore, a complete petrofabric study involves not only detailed laboratory studies and measurements, but also detailed mapping and quantitative data from the field.

Petrofabrics, then, is nothing more than very detailed structural geology and petrology. As in Billings' book, attention in this country has commonly been focused on grain-orientation studies and diagrams. However, these are no more than an added technique, to be used where other techniques fail, to supplement other results, or to check interpretations.

In igneous and sedimentary petrology, variation-diagrams and heavy-mineral correlations are somewhat analogous to grain-orientation diagrams. They require a great deal of tedious work and are therefore not used unless other data fail to give a positive answer and it appears that these techniques might.

So with petrofabric diagrams; they are used only when it appears that the results obtained will justify the extra expenditure of time. Sander is commonly thought of in this country as applying such diagrams to any and all problems. He has made a wide variety of applications, but in a collection of 30 of his reprints, 22 contain not a single diagram. In the longest one, 180 pages, there are only eight orientation-diagrams out of 54 illustrations.

Two "schools of thought"

It is unfortunate that there is widespread opinion in this country that within the realm of structural petrology there are two schools of thought, and that the tenets of the one are largely incompatible with those of the other. As a matter of fact, the differences are purely questions of emphasis and not of fundamental tenets at all.

The so-called CLOOS school, headed by HANS CLOOS, emphasizes detailed field-study and the embodying of the resultant measurements in maps so that the primary data can be seen at a glance. The so-called SANDER school emphasizes detailed laboratory observations and measurements and their correlation with field-data. Actually, neither of these groups is a "school of thought." The ideas and techniques are, for the most part, not new. The Scandinavian, Scottish,

and Alpine geologists of the last decades of the nineteenth century measured and plotted on maps cleavage, bedding, and even lineation, and made advanced structural interpretations from their data. About that time microscopical petrography was in its big upswing. Everything about a rock could be explained by careful description of a few thin sections. In the resulting rush to grab specimens and have thin sections made, detailed field-measurements were lost sight of and structural geology was set back at least a generation.

SANDER'S paper of 1911 [2] on the relation between differential movement and fabric is regarded by some as having established the foundations of structural petrology out of a clear sky, which, of course, is not the case. In the paper itself many of the ideas are ascribed to HEIM, BECKE, LEHMAN, and others. One of the most important ideas, namely, that it is possible to tell the direction of motion from a detailed study of micro-fabric, goes back at least to 1858, when it was mentioned by NAUMANN [3]. The statistical study of grain-orientation was developed as a new technique during the mid-twenties by SANDER and SCHMIDT and summarized by them in the early thirties, SANDER [4] and SCHMIDT [5]. However, the idea was not new. Preferred orientation of quartz had been observed microscopically at least 20 years earlier by TRENER [6] and by LEITH [7], and mineral parallelism observable megascopically was recorded by NAUMANN [8] and others more than a hundred years ago.

Structural geology and microscopical petrography in the United States more or less grew up together. Therefore, this emphasis on quantitative measurements has struck most of us as something entirely new instead of as a broken thread picked up again. Comparatively few papers published in this country prior to 1903 have maps with dip and strike symbols. From 1903 to 1930 less than half have such symbols. Even now there are very few that show lineations. Only one State Geological Survey requires that these things be put on maps, and, although the United States Geological Survey has a uniform system of structure symbols, it leaves to the judgment of the individual author the question of whether any symbols at all shall be put on a given map.

In the Bulletin of the Geological Society of America from 1930 to 1936 only 17 of 40 papers with geologic maps had any kind of dip and strike symbols and less than half of these 17 had detailed data. From 1937 through 1943 the situation is reversed, except for one year. The totals are 74 papers containing maps with dip and strike symbols, 52 with none. It should be emphasized that this includes only papers containing maps where dip and strike symbols would have been appropriate and useful, and that the figure 74 includes every paper that had even one map with one symbol. Again, there are comparatively few giving detailed data.

As indicated above, a part of this lag is due to the simultaneous development of structural geology and microscopical petrography in this country. Part of it can be ascribed to the fact that a great deal of the early geological work was necessarily reconnaissance in a country the size of the United States of America, with so few geologists available Still another part of it may also be attributed to the horror that geologists appear to have for anything quantitative, either mathematics or elementary physics and physical chemistry. Many "hard rock" geologists are inclined to poke a little fun at the paleontologists for breaking their "strategic fossils" up into endless species and subspecies. However, when a paleontologist describes a new species of Waagenoceras he at least counts the volutions and gives the dimensions of each in millimeters. He is measuring what he can, which is more than the petrologist does when he guesses that the magma from which a given rock was derived may have contained 0.08 per cent or eight per cent of water, and more than a structural geologist does when he postulates the direction of application of force that produced a given metamorphism without even determining the direction of motion during the metamorphism.

Geology can never be an exact science in the sense that mathematics and physics are. However, it can make use of the exact sciences to provide much more definite and quantitative answers than we now have to a great variety of questions. That it has not done so already is due largely to the youth of geology as an independent science. Many of the professors who are still holding forth were trained during its infancy when very few indeed realized the importance of physics and chemistry to a geologist. Therefore, they fail to see that their students are properly grounded in these things, either through carelessness or ignorance. These students in turn become teachers and the cycle is repeated, which slows up the advance of science tremendously.

On the other hand, there are many young teachers and some of the older ones who not only encourage their students to take physics, chemistry, and mathematics but insist that they do so; also that they learn to make accurate observations and measurements in the field and laboratory. A large percentage of our geological publications come from our State and Federal surveys. A lower percentage of these publications contain structural data on maps than do the papers emanating from private educational and research institutions. This can in part be ascribed to the fact that tax-

supported bureaus must put first the work that the public wants done and therefore frequently find themselves without time to do a given job with sufficient detail. Another part, however, is due to the natural tendency one has to sit down and stop learning once a (more or less) permanent connection with one of these bureaus has been attained.

Petrofabrics, then, is nothing new and radically different. The same things are measured these structural geologists have measured for decades. Petrofabrics merely seeks to systematize that data and to apply some of the methods of physics and mathematics to their interpretation.

The saying attributed to LAPWORTH, "Map it right and it will come out right," is very much to the point. However, if the map is purely two-dimensional, that is, if it merely shows the areal extent of the various geologic units, there are likely to be two or more interpretations that could fit the known facts equally well. But if all measurable structural elements are put on the map, that is, if it is made as nearly three-dimensional as possible, the chances are much better that there can be only one interpretation. The map of the Clove Quadrangle and part of the Carmel Quadrangle in eastern New York and western Connecticut by ROBERT BALK [9] is a beautiful example of this kind of mapping.

Petrofabric diagrams

The technique of preparing statistical grain-orientation diagrams is relatively new That is probably why so many geologists shy away from their use. It is certainly not because the methods of preparation are complicated; it is much easier to learn to measure and plot the orientation of uniaxial or platy minerals than it is to learn to obtain and interpret interference-figures from biaxial mineral grains in rock-sections. Yet any petrographer can interpret such figures when they are moderately well centered, and many do not hesitate to interpret them when they are completely uninterpretable! The preparation of x-ray diagrams and diagrams from biaxial minerals is somewhat more complicated, and their chief horror is also their novelty.

Since these diagrams constitute the chief innovation in petrofabrics, let us consider them somewhat more in detail. Just how tedious is their preparation? Are they worth the time and trouble that it takes to prepare them? Tables 1 and 2 give a moderately complete list of published diagrams.

It is difficult to estimate the amount of time required to prepare an "average" diagram for publication. It depends not only on the mineral selected, and on the individual doing the work, but also on grain-size, percentage of the mineral in the thin section, degree of preferred orientation, other minerals present, etc. However, two working days would probably be a maximum average time from mounting the thin section until the diagram is finally drafted, complete with legend, for publication. If we take this figure, it is seen that all published diagrams could probably have been prepared with a total expenditure of between 4000 and 5000 man-days. One man could have prepared all of them in something like 15 years of normal working time.

If these figures are set against the hundreds of thousands of unoriented sections that have been made and studied it will be seen that the use of orientation-diagrams is truly in its infancy. However, it is tedious to measure 400 grains of one mineral from one thin section, and there is little point to spending two full days or more on a single thin section unless the information gained

Table 1--Grain-orientation diagrams prepared with the aid of the universal stage

Mineral	No.	Mineral	No.
Quartz	900	Chlorite	15
Calcite	225	Pyroxene	7
Biotite	188	Scapolite	6
Muscovite	169	Epidote in albite	4
Olivine	81	Potassium feldspar	3
Plagioclase	69	Fluorite	3
Mica in feldspar	57	Quartz in feldspar	3
Gypsum	51	Kyanite	2
Mica	41	Aragonite	2
Dolomite	21	Nepheline	1
Anhydrite	18	Siderite	1
Hornblende	16	Total	1883

Table 2--Miscellaneous orientation-diagrams

Kind of diagram	No.
Joints	111
Grain-orientation diagrams made without universal stage	62
X-ray diagrams	37
Pebbles	27
Thrust-planes	12
Lineation	12
Schistosity	8
Tectonic axes	5
Fractures in quartz	3
Fractures in garnet	3
Bedding planes	1
Inclusions in rocks	1
Total	282

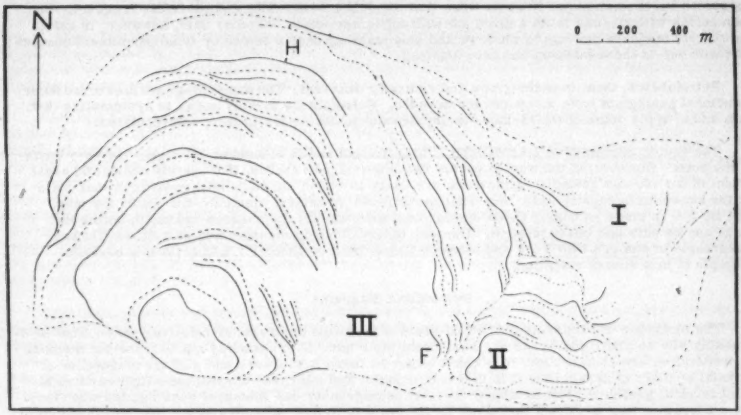


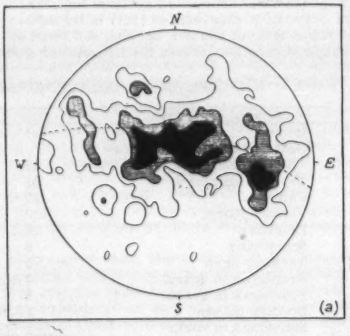
Fig. 1--Outline map of Nygård Pluton in Central Sweden [after Larsson (10)]

thereby is worth that much time. Is it? Is a heavy-mineral determination worth the time that it takes? Is a chemical analysis of an igneous rock worth the trouble? The answer to any of these questions depends upon the geologic setting, and upon the question or questions the answer to which is sought. The decision must be made after careful consideration of all the factors in a given situation. Many times it will not be possible to be sure in advance. In some cases the preparation of a diagram will be worth many times the effort spent; in others the time may be entirely wasted.

Use of petrofabric diagrams in geologic problems

The best way to get an idea of the sort of problems in which grain-orientation diagrams can help is to outline briefly some of the uses to which they have been put.

Igneous geology--WALTER LARSSON [10] has made a very interesting application of fabric analysis to the problems of differentiation and intrusion, and correlated the data thus obtained with pertinent structural and chemical data. He made a detailed geologic, petrographic, and chemical study of a small, but composite basic



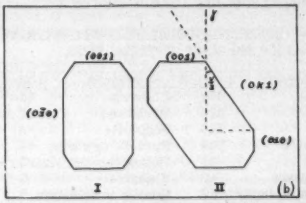


Fig. 2--(a) Fabric diagram of 300 hypersthene c-axes from specimen of norite taken near northern part of intrusion III shown in Figure 1 [(4-3)-2-1 o/o]; (b) schematic diagrams of forms of hypersthene crystals [after Larsson (10)]

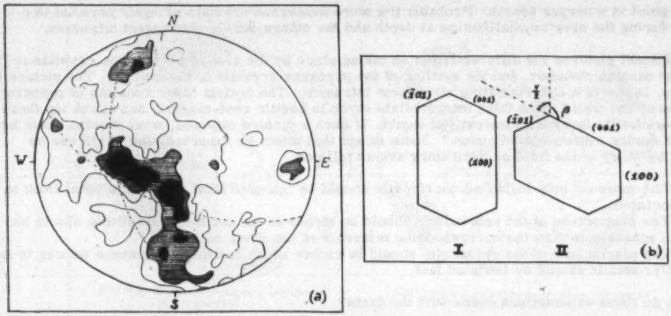


Fig. 3--(a) Diagram of 280 poles of pericline lamellae of plagioclase crystals from anorthosite from eastern part of intrusion III of Figure 1 [(5-4-3)-2-1 o/o]; (b) schematic diagrams of forms of plagioclase crystals [after Larsson (10)]

intrusion in central Sweden.

The intrusion is a compact and simple one, but detailed mapping of internal structures reveals the presence of three distinct intrusions, separated by brecciated zones (Fig. 1). The rocks are largely noritic but there are layers of pyroxenite, gabbro, and anorthosite.

The relative ages are suggested by the intrusive contacts, but LARSSON says that chemical, mineralogical, and structural data point to the same order. For example:

(1) The intrusions become richer in SiO_2 in the order I, II, III.
(2) The earlier intrusions are more uniform in composition, that is, they are not so highly differentiated as is III.
(3) The layers dip more steeply in the earlier intrusions and flatten out in the last one. LARSSON believes this to be a general rule and uses it in the interpretation of the feldspar orientation-diagram.

LARSSON measured the orientation of 300 hypersthene crystals from a specimen taken near the northern border of intrusion III and of 300 plagioclose grains from a specimen collected near the eastern border of the same intrusion.

Figure 2a shows the hypersthene diagram prepared from the c-axes. The plane of the layering strikes almost east-west and dips steeply to the north. The diagram shows three distinct maxima. The principal maximum lies in the flow line of the layer and is interpreted as being done due to the orientation by flowing of crystals elongate parallel to the c-axis. The two smaller maxima are also in the plane of the layering and are symmetrically disposed with respect to the principal one. These maxima can be explained by assuming that some of the grains were elongate parallel to the face (011) (see Fig. 2b).

Before we consider what this may mean in terms of differentiation and intrusion let us consider the feldspar diagram, Figure 3a. This diagram is much like that for hypersthene except that there are two sets of maxima arranged in two intersecting planes. The one that strikes more nearly east-west is probably older because (1) the maxima in it are fainter, indicating a certain amount of over-printing by the later movement, and (2) that plane dips more steeply than the other.

The maxima are explained exactly as are those for hypersthene; the principal maxima that coincide with the flow-lines are from crystals elongate parallel to their c-axes, the submaxima to crystals elongate parallel to a. The angular relations are correct for such an interpretation; the measured angle between the submaxima in the diagram is 126° (V/2 in Fig. 3b) = 63° 57′.

Now, what is the meaning of these things for differentiation and intrusion? Two different crystal forms probably mean a change of physico-chemical conditions, which could be brought about by intrusion to a higher level after crystallization and differentiation had proceeded to a

certain point in a deeper hearth. Probably the more numerous crystals elongate parallel to c formed during the slow crystallization at depth and the others during subsequent intrusion.

LARSSON pictures the differentiation as taking place by the rise of plagioclase crystals to the top of the magma chamber, and the settling of the pyroxene crystals to the bottom. The picture he has, then, is one of a differentiating stratiform intrusion. The bottom layer consists of pyroxenite with interstitial liquid. The thick intermediate layer is noritic rest-magma, and at the top there is an anorthositic layer with interstitial liquid. If such a picture obtained, what results would be expected during subsequent intrusion? Some things that might be expected, and which can be checked by study in the field or laboratory are as follows:

(1) The more or less solidified anorthosite should be intruded first and should be at least in part brecciated.
(2) The plagioclase of the anorthosite should be richer in An and the hypersthene should be poorer in magnesium than the corresponding minerals of the other rocks.
(3) The plagioclase of the pyroxenite should be richer in Ab and the hypersthene poorer in iron.
(4) Pyroxenite should be intruded last.

How do these expectations check with the facts?

(1) The earliest layers intruded in III were along the northern border, away from the center of intrusion. They consist of norite with fragments of anorthosite. Where this norite is layered the thinner intermediate layers are anorthosite. To the southwest the layers become richer in pyroxene until in the southwest part of the intrusion there are layers and fragments of pyroxenite.

(2) The plagioclase of the anorthosite is richer in An and the hypersthene is poorer in Mg than the corresponding minerals of the other rocks. These relations are reversed for the pyroxenite.

(3) In the intermediate rocks (norite and gabbro) the plagioclase and hypersthene show intermediate compositions.

(4) Thus, the orientation-diagrams supplement the chemical and structural data to present a connected and logical story of the differentiation and intrusion of a layered basic intrusion.

Problems in sedimentation--Comparatively little fabric work has been done on sediments and sedimentary rocks. The type of thing that can be done is illustrated by work on shapes of quartz-sand grains. WAYLAND [11] showed that even in well-rounded quartz sand the grains are prolate spheroids, and that there is a distinct tendency for the long axes of the spheroids to be parallel to the c-axes of the quartz grains. He also showed that the c-axes of the grains lie in, or at a small angle to, the bedding plane, and also show a pronounced preferred orientation in the plane.

INGERSON and RAMISCH [12] showed that this elongation is probably due to original grain-shape and not to fracture or differential abrasion. They also demonstrated another characteristic elongation of quartz grains parallel to the unit rhombohedron, which can be an original shape, or produced by breaking of original grains.

These papers, and work on quartz orientation in ripple-marked sandstones [INGERSON, 13] show that quartz-orientation studies in sandstone can probably reveal the direction of the current during deposition, even when primary structures like ripple-mark and cross-bedding are absent.

Among other applications of these methods to problems of sedimentation may be mentioned studies of stream deposits and pebbles by KRUMBEIN [26 and 27] and applications to glacial geology by SCHARF [28] and RICHTER [29 and 30].

Problems of metamorphic rocks--Most of the published work has been on metamorphic rocks. This is due principally to the fact that the differential movements involved in the formation of most such rocks produce a higher degree of preferred orientation of the mineral grains than is commonly encountered in other types of rocks.

There are a great many types of problems concerning metamorphic rocks to which fabric diagrams are applicable, and many of these applications have already been made. A study by SAHAMA [14] illustrates the use of petrofabric methods in obtaining the deformation-pattern in a reconnaissance study of a large area where there are many different geologic units. It also shows how the effects of different periods of metamorphism can be separated and their relative ages determined.

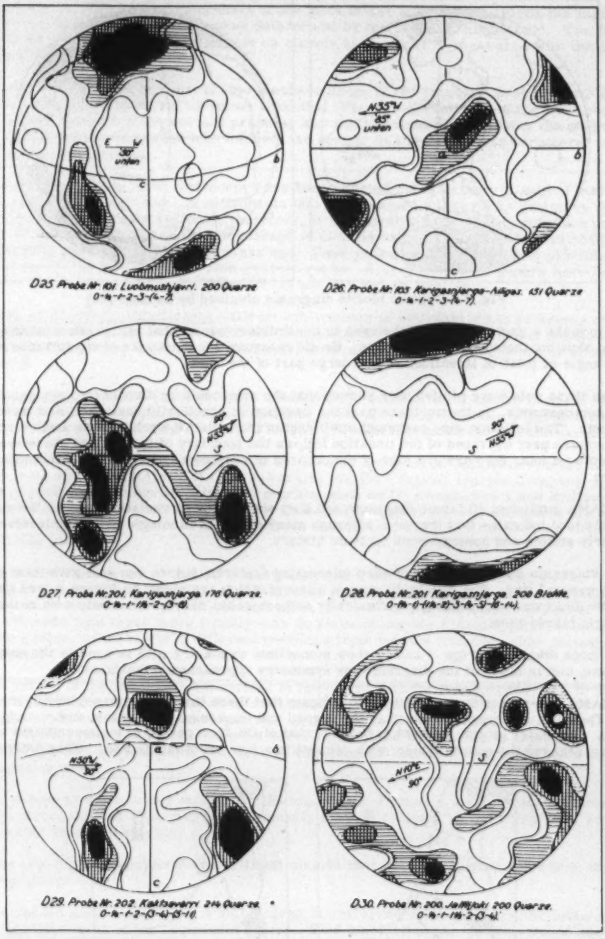

D 25. Probe Nr 101. Luodomushjavri. 200 Quarze
D 26. Probe Nr 103. Karigasnjarga-Aidjas. 131 Quarze
D 27. Probe Nr 201. Karigasnjarga. 176 Quarze.
D 28. Probe Nr 201. Karigasnjarga. 200 Biotite.
D 29. Probe Nr 202. Kaitsaverri. 244 Quarze.
D 30. Probe Nr 200. Jeltijoki. 200 Quarze.

Fig. 4--Typical quartz diagrams and one biotite diagram obtained by Sahama [14]

SAHAMA made a study of a tremendous granulite area in Lappland. The area is 300 km long and from 40 to 90 km wide. It is an arc extending in a general north-south direction with a convex side facing to the west.

The units are highly variable and it would seem to be almost impossible for one man to make anything of so large an area that was practically unknown when he went into it. SAHAMA did not

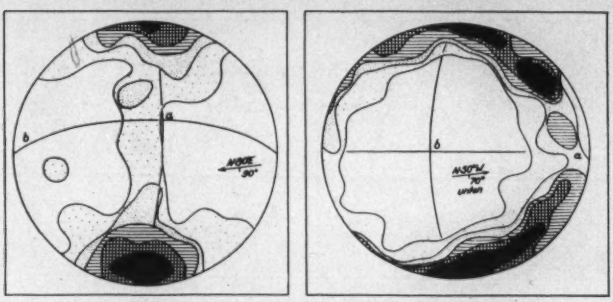


Fig. 5--Typical biotite diagrams obtained by Sahama [14]

attempt to make a geologic map of the area in the ordinary sense, that is, by selecting mappable units and showing their areal distribution. He did measure dip and strike of the foliation and direction and angle of pitch of lineations over a large part of the area.

When these data were plotted they showed that the area could be divided into two parts that are roughly homogeneous. In the northern part the lineation is practically horizontal and trends almost north-south. The foliation dips eastward at all angles from almost horizontal to almost vertical. In the southern part the trend of the lineation follows the boundary of the arc and therefore varies from northwest near the northern part of the subarea to northeast in the extreme southeastern part of the arc.

SAHAMA published 80 fabric diagrams and they show no more variation than do the megascopic data. This fact indicates that the area, although many different lithologic units are involved, has had a fairly simple and homogeneous tectonic history.

The diagrams show a number of very interesting features, but we can deal with them here only in a very general way. The quartz diagrams, a few of which are shown in Figure 4, are almost all two-girdle diagrams and, although intrinsically orthorhombic, they are triclinic with respect to the megascopic fabric axes.

The mica diagrams (Figs. 4 and 5) show monoclinic symmetry with respect to the megascopic fabric axes, and in many of the diagrams the symmetry approaches orthorhombic.

SAHAMA interprets these relations to indicate that there have been two periods of metamorphism. The first was more intense than the second and impressed both quartz and mica fabrics on the rocks. The later motion was not parallel to that of the first period of metamorphism and largely rearranged the quartz fabric, with respect to a new set of fabric axes. This deformation was

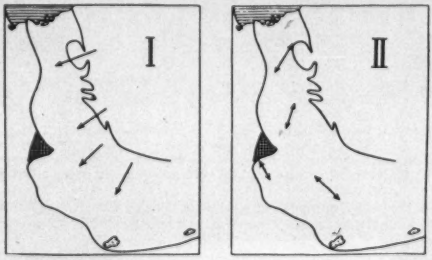


Fig. 6--Outline map of granulite area in Lappland studied by Sahama [14]

not intense enough to effect a rearrangement of the mica fabric and for this reason the megascopically visible fabric axes are the older ones determined by the original mica fabric. The B-axes determined from the mica diagrams coincide as closely as they can be measured with the B-axes as determined in the field.

These data led SAHAMA to separate the metamorphism of the granulite area into two different phases, with considerably different direction of motion (Fig. 6). The motion of the first period was almost radial with respect to the arc and probably was instrumental in developing the shape of the area. The second period was much less intense; the motion was more or less peripheral and affected only the quartz fabric.

Up to the present time, most fabric work has been carried out by means of optical methods on moderately coarse-grained rocks. It is probable that fine-grained (clay) rocks are more sensitive to metamorphism than are coarser ones; therefore, it is desirable to be able to measure preferred orientations in these rocks, where the microscope is of little or no use. SANDER and SACHS [15] published the first paper in this field 14 years ago. Four years later SANDER [16] published a detailed optical and x-ray study of some fine-grained rocks. A very few other papers have been written in this field, two of which, FAIRBAIRN [17 and 18], are in English.

Problems of economic significance--Direct applications of petrofabrics to problems of economic significance are almost non-existent. FAIRBAIRN [40] lists a number of possible applications to mining problems, but they are all suggestions of things that can be done, or at least should be tried.

(1) Ore minerals--ROBERTSON [19] has measured the orientation of an ore mineral (sphalerite), and the relation between its orientation and that of the enclosing dolomite suggested the mode of origin and deformation of the sphalerite. TUTTLE [20] has measured the orientation of ilmenite.

(2) Lumar--Perhaps the most striking and successful commercial application of the methods of fabric analysis is that by BAIN [21]. While working for the Vermont Marble Company, he studied the relation of fabric to various properties of marble, such as (1) transparency and brilliance, (2) weathering, and (3) strength and rigidity. BAIN finds that transparency and brilliance are affected by (a) grain-orientation, (b) nature of the intergrain boundaries, and (c) mineral composition, especially coloring matter.

(a) The extraordinary ray of calcite is much less absorbed than is the ordinary ray. The extraordinary ray is the one whose direction of vibration is parallel to the c-axes of the crystal. Therefore, marble slabs that show a marked concentration of the c-axes of the calcite grains in the plane of the slab transmit light much more readily than do slabs of marble without preferred orientation of the calcite grains, or slabs cut in different positions from marble that does show strong preferred orientation.

(b) The nature of the intergrain boundaries is important both for transparency and brilliance. Brilliance is imparted to marble, just as to a diamond, by repeated reflection of light at boundaries between media of different indices of refraction. If the layers of air between grains average less than 2 $\mu\mu$ in thickness total reflection does not occur readily and the marble is glassy and lacks luster. If the layers of air are more than 5 $\mu\mu$ in thickness the transparency is cut down so much that the marble is waxy.

(c) The nature of the coloring matter is also important. Opaque minerals cut down transparency, of course, but non-opaque colored minerals such as chlorite, mica, amphibole, or quartz impart desirable colors to marble.

For this new highly translucent and brilliant marble that is called Lumar there are, therefore, three prerequisites:

(a) The calcite grains must show a high degree of preferred orientation and the slabs must be cut parallel to the c-axes of the component grains. This orientation can be determined accurately from grain-orientation diagrams, which obviates the tedious method of cut-and-try.
(b) The intergrain boundaries must lie between 2 $\mu\mu$ and 5 $\mu\mu$ in thickness.
(c) The coloring matter must be in the form of non-opaque materials.

(3) Weathering of marble--BAIN [22] finds that weathering of a marble surface is affected by at least three features of the fabric (information on weathering and strength taken from unpublished reports kindly lent by Professor BAIN).

(a) The orientation of the grains is again important. The most resistant faces are those that are cut normal to the largest number of c-axes because (1) the basal pinacoid is the least soluble face of a calcite crystal--the rhombohedral face is the most soluble--and (2) faces cut normal to the c-axes are cut by fewer twinning and cleavage planes than any other, hence moisture penetrates them less readily than faces cut in other directions. Therefore, a marble slab cut so that it will resist weathering on the face to best advantage must be cut at right-angles to one from the same specimen that is intended to pass light to good advantage.

(b) The nature of the intergrain boundaries is also of importance in weathering. Marble with narrow and complex intergrain boundaries resists weathering much better than does marble that has more or less rounded grains with comparatively wide spaces between the grains.

(c) Marble of uniform grain-size weathers better than marble with grains of different sizes.

(4) Rigidity of marble--Rigidity and strength also depend upon the grain-orientation and the intergranular. BAIN indicates that the fabric influences strength, but has not determined relative strengths of a given specimen in different fabric directions. Most of his experiments compare the rigidities of different samples that have different fabrics.

His experiments established the definite relation that rigidity is inversely proportional to the absorption. In other words, a specimen that has a good deal of pore-space with the pores large enough to absorb water will have low rigidity.

Thus we see that three of the most important properties of marble are directly dependent upon grain-orientation and the nature of the intergranular--two important elements of the fabric of a rock. These studies are of practical importance in (1) determining for what purposes an unknown marble is suited, (2) grading and mapping quarries that are in operation, (3) eliminating experiment in determining the directions in which slabs should be cut for various purposes, etc.

(5) Strength of building materials--Another use of fabric analysis that has a direct bearing on practical problems is the relation of the strength of building stones to fabric. A number of such studies have been made; several papers dealing with the subject have been published in scientific journals, and at least one in a trade journal devoted entirely to the stone industry.

SANDER and some of his coworkers at Innsbruck published the first such study in 1929 [23]. They took a nearly structureless marble of unknown fabric and prepared a random thin section from it, whose orientation, however, was known with respect to the remainder of the specimen. The diagram prepared from that section indicated clearly the position of the B-axis. A poor foliation could be made out parallel to that axis and thus the three fabric directions were determined.

Cubes were cut with their faces normal to the fabric axes as determined from the diagram, and the cubes were subjected to crushing-strength tests. The results are shown in Table 3. The greatest strength is parallel to the c-axis.

HOLLER [24] made a number of tests on rocks of different kinds, testing some of them both by compression and by impact. He found differences amounting to almost 50 per cent of the maximum crushing strength and to about 70 per cent of the impact strength of the most highly anisotropic specimen depending upon the fabric direction in which the force was applied.

The first rock that HOLLER tested was a diabase and the fabric directions were determined from the foliation and the cross joints. (Foliation = ab; cross-joints = ac; which determines all three fabric axes.) The diabase showed the greatest strength parallel to a; least parallel to c, as shown in Table 3.

The next specimen was a granulite that, unlike most granulites, was not highly foliated; ab could be determined in the hand specimen, but b was determined under the microscope. The fabric directions showed the same relative strengths as those of the diabase, but with much greater numerical differences, as seen in Table 3.

The fabric of the pyroxene granulite had to be determined entirely from microscopic data. It shows a strength anisotropy intermediate between the diabase and the quartz-feldspar granulite.

The basalt showed a flow-structure that was confirmed under the microscope; b was determined from a diagram. The strength was much like that of the diabase.

Table 3--Relation of strength of rocks to fabric

Investigator	Material	Compression			Impact		
		a	b	c	a	b	c
Sander, et al.	Marble	1118	1291	1470	...	...	...
Holler	Diabase	1876	1705	1607	...	...	...
Holler	Granulite	3467	3225	1778	79.22	36.23	21.33
Holler	Pyroxene granulite	2655	2650	1924	31.88	26.33	18.46
Holler	Basalt	3209	3208	2508	49.2	13.4	17.35
		H	K	L	L, K, and H are the best, poorest and intermediate parting surfaces, respectively.		
Holler	Diorite hornfels	3260	2990	2000			
Holler	Diorite hornfels	H′	K′	L′	K′ is a microscopic foliation that is almost parallel to K. H′ and L′ are normal to K′ and to each other.		
		2700	3300	2800			
		∧ ab	b	c	ab = foliation; c ⊥ ab		
Bell	Granite	2090	2430	2170	a = direction of motion b ⊥ a in ab		

The two sets of experiments with the hornfels show that a slight difference in the orientation may mean a big difference in strength. HOLLER does not give an angle in degrees between K and K′, but says that "K′ is almost parallel to K, but is inclined to it at a definite angle."

BELL [25], working at Munich, made a similar study of a slightly foliated muscovite-biotite granite. His results are consistent with those of HOLLER as far as they go, but BELL did not determine the strength parallel to the a-axis. The granite is stronger parallel to b than parallel to c, just as the rocks tested by HOLLER were. The third set of tests was made on blocks cut at an angle of 45° to ab and these blocks had less strength than any of the others. This was to be expected, because the mica flakes lie predominantly in ab.

The results with igneous and quartz-feldspar-mica metamorphic rocks are different from those with marble, in that a and c change places, c being the strongest direction in marble, and the weakest in the other rocks. This difference is probably caused by the difference in the behavior of calcite and mica, possibly because calcite has three glide planes and mica only one.

BELL also measured the fractures in the deformed granite. He found that only 17 per cent of the total length of the breaks is between grains, which is contrary to what had previously been thought. He also found that a larger percentage of fractures traverse mica than any other mineral, taking into consideration the percentages of all the minerals present in the rock. This was to be expected and shows that building stones with a high percentage of flaky minerals should be avoided if great strength is desired. These studies also indicate that the shape of particles used in making concrete and cement is important in determining strength, and that the relation between the orientation of a block during setting and its orientation in use may be significant.

Spherical projection as an aid in solving structural problems--Spherical projection can be of considerable aid in solving structural problems directly, as well as indirectly by its use in preparing grain-orientation diagrams. Problems involving angles between lines and planes, but not distances, can be solved more easily and rapidly by this method than by any other yet devised. Even when distances are involved, spherical projection can be used to advantage in solving the parts of problems concerned with angular relations.

Several papers have been published recently in which this method is applied to particular problems. A more general treatment by BUCHER [31] has recently appeared.

A comparison of the amount of construction required for the solution of a typical structural problem by descriptive geometry and by spherical projection will illustrate the advantages of the latter. Such a problem is found in BILLINGS [1, pp. 440-442]. The problem: "A vein that strikes north 40° east and dips 40° northwest intersects a vein that strikes north 30° west and dips 55° northeast. What is the attitude of the intersection?" Figure 7 (BILLINGS' Fig. 329) shows the

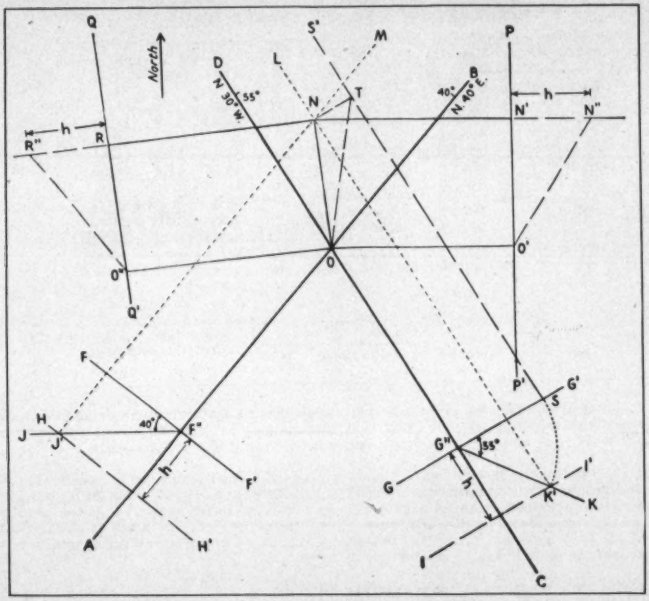


Fig. 7--Construction used by Billings in solving problem of determining attitude of intersection of two veins whose dips and strikes are known (Fig. 329 of Billings, Structural Geology, Prentice-Hall, New York, 1942, reproduced by permission of the publishers)

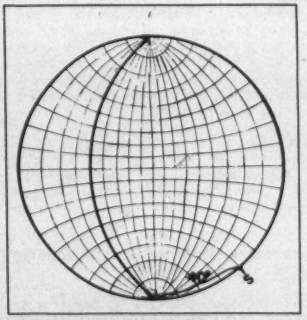


Fig. 8--Position of net and tracing paper for drawing great circle representing a vein N 40° W 40° NW

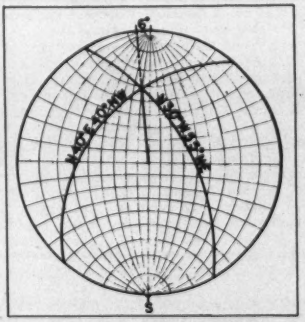


Fig. 9--Method of determining direction of pitch of line of intersection of two planes

construction required to solve this problem by descriptive geometry. There are 22 construction lines, and 39 letters, not counting those used to indicate dip and strike. Statement of the solution requires a page and a half of print.

Contrast this with the stereographic solution which requires three construction lines and four simple movements of the piece of tracing paper on which the solution is made.

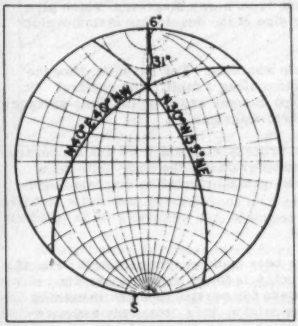


Fig. 10--Method of determining angle of pitch of line of intersection of two planes

(1) Turn the paper until its orientation-arrow is 40° east of the S-point of the net. Draw the great circle that is 40° from the left side of the net (Fig. 8). This great circle represents the vein that is north 40° east 40° northwest.

(2) Place the arrow 30° west of the S-point and draw the other vein 55° from the east side of the net. The intersection of these two great circles is the projection of the line of intersection of the veins.

(3) Place the arrow at the S-point of the net (zero-position) and draw a line from the center of the net through the point of intersection of the great circles to the periphery of the net (Fig. 9). This line gives the direction of pitch of the intersection, north 6° west in this example.

(4) Place the line through the intersection either on the equator or zero-meridian of the net (Fig. 10) and read the angle between the point and the periphery of the net, 31° in this example. The intersection of the veins pitches 31° north 6° west.

This solution can be made in less than two minutes, including the time taken to mount the tracing paper and to record the angles.

Petrofabric diagrams as an aid in mapping--There are types of problems in which fabric diagrams should prove useful, but in which little or no use has yet been made of them. These diagrams can be useful in mapping where associated geologic units cannot be readily told apart in the hand specimen or thin section, but have distinctive fabric characteristics. For example, suppose that we are working in an area of folded metamorphic rocks. A fault traverses the area and we

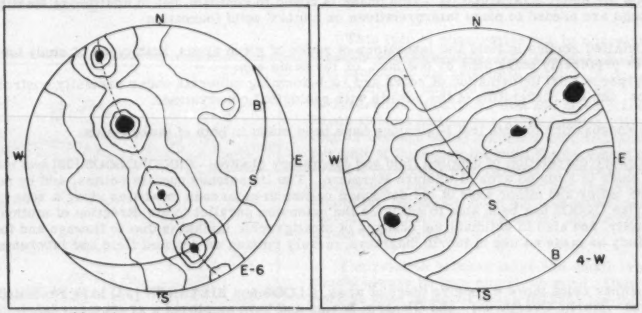


Fig. 11--Theoretical grain-orientation diagrams from either side of fault in hypothetical problem discussed in the text

wish to trace its outcrop as closely as possible. The fault trends north-south and to the west of it the fold axes trend northeast-southwest;tto the east, northwest-southeast. In areas where outcrops are poor and megascopic structure is not evident it is not possible to locate the fault in the field. It is found, however, that the rocks on either side of the fault consistently give the orientation patterns shown in Figure 11. By preparing a few diagrams, therefore, it is possible to locate the

fault as closely as the outcrops permit at a given place. It should be noted that it is not necessary to spend two days on such a diagram. Enough grains can be measured in an hour to see which pattern is developing.

The rocks on opposite sides of the fault may show different types of diagrams rather than the same type with different orientations.

In fine-grained rocks it should be possible to plot isograds from x-ray diagrams, which give an indication of the degree of preferred orientation and of the size of the developing metamorphic minerals (suggested by W. W. RUBEY).

In other types of fault-problems diagrams can give no help whatever. For example, take the common problem in mining--to determine the direction of motion along a fault. The ruptural deformation of faulting does not reorient mineral grains (except in some cases on the fault-surface); therefore, the motion along the fault is not reflected in the fabric diagrams.

In short, fabric diagrams can be of use when the geologic process with which we are concerned has produced a demonstrable preferred orientation of the mineral grains in the rock-units being studied. When no such preferred orientation has been produced, grain-orientation diagrams obviously cannot yield information about the process.

Interpretation of diagrams

By comparison--Many of the existing interpretations have been made purely by comparison of orientation-diagrams. The process is somewhat like this: Rock A is found to have a certain orientation pattern for quartz. Rock B has a very similar pattern for quartz. If there is nothing in the field-relations, or other observed data, to contradict the opinion, it is commonly assumed that B was deformed under conditions similar to those under which A was deformed. As examples accumulate, the diagrams are divided into more or less set types, and when a new diagram is prepared it is likely to be compared with a generalized type rather than with a diagram from some particular rock.

This descriptive and comparative phase of petrofabrics has been in progress for almost 20 years and, as we have seen, more than 2000 fabric diagrams have been published. Thus, fabric analysis is in a stage resembling that in which igneous petrology found itself in 1890; much descriptive work had been published, but there had been very little experimental work upon which to base interpretations.

Needs for better interpretation--This phase is bound to continue, but in addition at least two other things are needed to place interpretations on a more solid foundation:

(a) Detailed studies in field and laboratory of rocks of given areas, both types of study for a given area preferably being done by one man, or the same men.
(b) Experimental deformation of rocks and rock-forming minerals under carefully controlled conditions, and the correlation of the results with geological observations.

It is encouraging to note that beginnings have been made in both of these fields.

(1) Closer correlation of detailed field and laboratory studies--ERNST CLOOS [32] has made a detailed study of a folded area in western Maryland. The limestones contain öolites, and by measuring the major and minor axes of the deformed öolites at numerous localities along a zone normal to the strike CLOOS has been able to estimate the extension parallel to the direction of motion at each locality, and also to estimate the changes of stratigraphic thickness due to flowage and folding. In this study he made no use of fabric diagrams, merely relying on detailed field and laboratory work.

In another much more extensive piece of work, CLOOS and HIETANEN [33] have restudied the area of the "Martic Overthrust" and Glenarm Series and have employed a great many fabric diagrams to make interpretations more precise.

The amount of detail that is observed during a given study will depend in large part on the scale that is used, which will in turn depend on such things as the size of the area and time and personnel available. In general, one will not measure more details than can be put on a map. Therefore, more joints, foliation-planes, fold-axes, etc., will be mapped on a scale of 1:1000 than on 1:24,000. Students should be taught to measure and record the important things, whether there

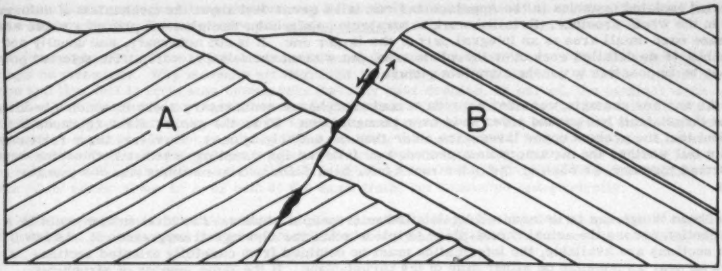


Fig. 12--Structure-section showing various age-relations (see text)

are only a few data recorded, as on a reconnaissance map, or whether it is filled with structural symbols, as on a detailed map of a quarry.

Relative ages are determined from field-relations in almost every area that is studied geologically. For example, take the structure-section shown in Figure 12. In a section like this, one would not hesitate to say that the sequence is as follows: (a) Rocks of A were deposited, (b) tilted, and (c) eroded; (d) rocks of B were laid down, (e) tilted, and (f) eroded; (g) the whole sequence was faulted; and (h) ore bodies developed along the fault.

In thin or polished section, however, the same man who makes the above field-interpretation without hesitation is likely to confine his discussion of order of events to a few more or less uncertain remarks about the order of formation of the minerals. In many sections this will be all that can be told, of course. However, in metamorphic rocks it is often possible to obtain from a thin section, or series of thin sections, a sequence of events that will be quite as positive, and important, as the ones obtained from field-evidence. The sketch of Figure 13 shows a hypothetical case. From this single thin section the following sequence can be deduced: (a) Deposition of A, (b) metamorphism and partial recrystallization of A; development of biotite, (c) folding of A, (d) continued recrystallization; development of muscovite, (e) formation of the s-zone, B, with partial reorientation of the mineral grains in the zone of movement, (f) formation and rotation of the porphyroblast, C.

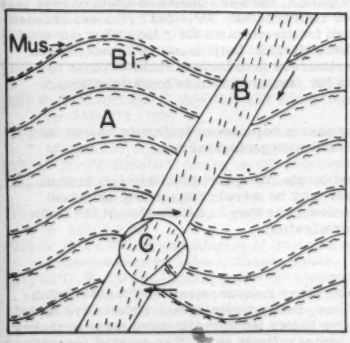


Fig. 13--Sketch of thin section showing various age-relations (see text)

This type of observation can be correlated directly with field-data. For example, MÜGGE [34] measured the amount of rotation of porphyroblasts in phyllite and calculated the amount of differential movement that had taken place between top and bottom of a given crystal. By getting an average value for horizontal displacement per unit of thickness the total displacement of the top of a formation with respect to its base can be calculated. The value thus obtained is always a minimum, because it does not take into consideration motion that took place before the porphyroblasts began to grow.

The relation between large and small areas should always be kept clearly in mind. Detailed work is done on small areas because the information thus gained can be used in interpreting much larger ones. By detailed study of a few thin sections BAIN can map a whole marble quarry according to type of material. By means of detailed study of a comparatively few small areas SAHAMA was able to obtain a fairly comprehensive picture of the deformation of an area thousands of square kilometers in extent. Detailed work in properly

selected isolated quarries in the Appalachians can tell a great deal about the mechanism of deformation in the whole province. Detailed work at strategic points helps decipher the plan of a whole area because each small area is an integral part of the larger one. It is not necessary, and usually not possible, to do detailed work over the whole area, but without the detailed work at the selected points it may be impossible to get the complete picture.

As another example, consider an area of metamorphosed sedimentary rocks in which a bedding plane thrust-fault has pushed older beds over younger ones. From the general field-relations it is evident that the present upper layers are older than the underlying ones. However, these relations do not tell whether the metamorphism preceded or followed the thrusting, whether both series were deformed together, or whether the older rocks have been deformed more times than the younger ones.

These things can be determined by detailed microscopic studies. The ideal set-up would be a thin section across the actual thrust-plane to tell whether the cleavage transgresses it. As few such sections are available, the information must be obtained from carefully oriented sections taken as near as possible on either side of the thrust-plane. If the same number of structures show up in similar rocks on both sides of the fault and if they have the same orientations, it is conclusive evidence that the cleavages transect the fault-plane and that the metamorphism is later than the thrusting.

If the orientation-plan of all of the minerals common to the two series of rocks is essentially the same for both, this is additional evidence that they were deformed together after the thrusting and that they have been subjected to the same period(s) of metamorphism.

If, on the other hand, the older rocks show s-planes not developed in the younger ones, and if the minerals, especially mica, show a different orientation-plan, the older rocks were deformed before the younger ones were laid down.

(2) Experimental deformation of rocks and minerals--In the laboratory study of rock and mineral deformation GRIGGS [35, other references in this paper], together with Mrs. KNOPF [36] and J. F. BELL [37], has made an auspicious beginning. Laboratory deformation of marble, with grain-orientation studies before and after deformation, confirmed the idea that calcite deformation takes place largely by gliding along $\{01\bar{1}2\}$ in the direction of [0001]. The direction of movement in a deformed calcite rock, therefore, can be recognized by the relation between the maxima of the optic axes and of the lamellae.

Deformation of single calcite crystals [GRIGGS, 38] gave the same mechanism of yielding, but the single crystals proved to be less ductile than the marble. This probably indicates that in a polycrystalline aggregate part of the deformation is intercrystalline.

GRIGGS and BELL tried the same sort of thing with quartz, but were unable to observe any evidence of translation gliding at pressures up to 138,000 atmospheres. Oriented cylinders crushed by directed pressure yielded a preponderance of elongated fragments with their long axes more or less parallel to the cylinder axes. They, and later FAIRBAIRN [39], built tentative hypotheses on the basis of these results to explain quartz orientations observed in deformed rocks. These hypotheses may provide a partial explanation, but the basis for interpretation is much less secure than for calcite.

This important work should be continued not only on quartz but also on feldspars, micas, and other groups of minerals, and the results closely correlated with geological data.

Fabric data also show how minerals deform; even minerals like quartz that have no demonstrable glide-planes. A few diagrams for a given mineral may be merely suggestive, but when some scores or hundreds of diagrams for one mineral accumulate they can have almost the same degree of certainty that attaches to an experimental determination.

Summary

Petrofabrics is concerned with detailed field and laboratory measurements and their correlation. Most of the ideas and techniques are by no means new, but accurate measurements are being reemphasized by workers in this field in an attempt to give better interpretations in many branches of geology. Fabric, or grain-orientation, diagrams are comparatively new. It is pointed out that these diagrams are no more than added technique for studying certain spatial relations whose determinations are difficult or impossible without them. It is also shown that by the use of these

diagrams some geologic interpretations can be made that are not possible without them and that other interpretations become more accurate, more certain, or more rapid by their use.

It is urged that accurate measurements be made wherever possible and that the important things be measured. Why measure stratigraphic thicknesses to a fraction of a foot in a deformed zone and then fail to recognize movements that may have doubled, or halved, the original thickness? Quantitative measurements should be made both in the field and in the laboratory. Field-relations suggest what things should be looked for and measured in the laboratory and independent laboratory experiments, the results of which can help in making field-interpretations. Likewise, the results of laboratory work can suggest new things to look for and study in the field. Closer correlation of these two lines of attack can bring about more rapid progress in many branches than could either alone, or even both at the same time, but conducted independently.

Why petrofabrics? Because it is the most quantitative approach yet developed for a variety of geological problems and can give information about many of them that cannot be obtained otherwise.

Acknowledgment--Dr. ERNST CLOOS has suggested that a paper explaining petrofabrics could serve a useful purpose just now. Some of the statistical data on numbers of papers published are taken from a compilation by him and he also made many helpful suggestions about material to be included. It is a pleasure to acknowledge this assistance by Dr. Cloos, as well as his kindness in reading a preliminary copy of the manuscript and the final copy.

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CORRELATION BETWEEN DEFORMATION-PLANES AND CRYSTALLOGRAPHIC DIRECTIONS IN VEIN QUARTZ FROM ANTIETAM QUARTZITE, MARYLAND

J. L. Anderson

(Abstract)

A qualitative study of the excellent fracture-patterns obtained in vein-quartz from the Antietam quartzite was made by means of the universal stage. The deformation-planes are fractures, some of which are characterized by straight, sharp walls, others are composite consisting of two or more planes, and a third type is curved. In some instances the fractures contain either recrystallized quartz or opaque and fluid inclusions. Pseudo-lammelar quartz was noted in several instances. The object of the study was to correlate the deformation-planes in the quartz with known crystal directions and to ascertain, if possible, the preferred directions of deformation.

The technique involved the orientation of the different planes and the plotting of the poles of these planes in an equal-area net, plotting being done in the lower hemisphere. The position of the crystallographic c-axis was also plotted. A "master sheet" containing the poles of all the important forms of the Trigonal Trapezohedral Class was constructed by plotting stereographically the poles of these forms in the lower hemisphere of an equal-area net. After studying and plotting the poles of the various deformation-planes and the c-axis, the c-axis was then rotated into the center of the projection and the pole of each deformation-plane was rotated accordingly. From this plot the planes can be identified by referring their poles to those of the master sheet.

The fracture-system of eight different grains was studied. It was noted that deformation produced certain preferred directions as well as several other subsidiary directions in the same crystal. The study confirms the facts, deduced both from experimental evidence and theoretical considerations, that the r, m, and c forms are important deformation-directions. It further indicates that the a, s, and d forms are also important directions along which fracturing occurs. The study revealed that fracture-systems of at least ten or more individual fractures parallel to r were noted six times; those parallel to z, twice; those parallel to m, three times; those parallel to c, three times; those parallel to a, four times; those parallel to s, three times; and those parallel to d and k, once each. The presence of these additional directions might have an important bearing on the interpretation of statistical diagrams.

The results suggest that quartz is a delicate indicator of metamorphism since the country rock in which the vein is contained is only slightly deformed and represents a low grade of metamorphism. The numerous fractures which traverse the grains have not affected their optical properties to any great extent. A higher degree of metamorphism would have caused crushing and recrystallization.

Note: The nomenclature to describe the planes in quartz used in this paper is as follows:

c is the basal pinacoid (0001)
m is the hexagonal prism, first order ($10\bar{1}0$)
a is the trigonal prism, second order ($11\bar{2}0$)
r is the positive first-order rhombohedron ($10\bar{1}1$)
d is the positive first-order rhombohedron ($10\bar{1}2$)
z is the negative first-order rhombohedron ($01\bar{1}1$)
s is the second-order trigonal pyramid ($11\bar{2}1$)
k is the ditrigonal prism ($51\bar{6}0$)

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THE INFLUENCE OF GRAIN-SELECTION ON THE MEANING OF QUARTZ-DIAGRAMS

Robert E. Fellows

Introduction--The most important factor which would reduce confusion in fabric analyses is the expanded use of partial diagrams. The purpose of this paper is to stress the significance of partial diagrams in a consideration of some confusing aspects of petrofabrics.

Any statistical study results in the accumulation of a mass of detail. In quartz-fabric analyses the detail consists of the measuring and plotting of thousands of quartz-axes; in an analysis of joints it consists of the measuring and plotting of thousands of joint-attitudes. In each case limiting factors are required to give meaning to the accumulated data. The study of joints, to be significant, must be confined to an area with well-integrated structural features. In quartz-fabric studies discrimination between grain-types is essential to the development of interpretable diagrams.

Partial diagrams, as distinct from composite diagrams, were recognized as requisites to the interpretation of rock-fabric by the early students, but emphasis was soon shifted to the improvement of technique with the result being an apparent disregard for some of the original fundamental principles. Partial diagrams are developed from measurement of grains selected according to types. These types are: Undeformed detrital quartz, peripheral-growth quartz, crush quartz, needle quartz, recrystallized quartz, and neocrystallized quartz.

Types of detrital quartz--The crystallographic orientation of a grain with respect to the direction of stress will affect the ease of rupture and the relative speed of recrystallization of the grain. When the grains have a random orientation prior to the application of stress, indications of recrystallization will appear in some grains sooner than in others. A detailed study [see 1 of "References" at end of paper] of quartz-rich rocks ranging from undeformed types to recrystallized quartz revealed five separable quartz types each indicating a different degree of recrystallization.

Undeformed detrital grains are "those discreet particles which have resisted deformation by fracturing or granulation. They commonly display strong strain-shadows and dusty inclusions. Their borders are usually delineated by a rim of dust which suggests the etched and dirt-filled surface of the original detrital fragment. Grains show all gradations of roundness and angularity. The texture is generally inequigranular since fine-grained crush quartz is a common associate of

Fig. 1

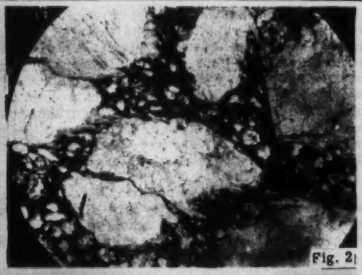
Fig. 2

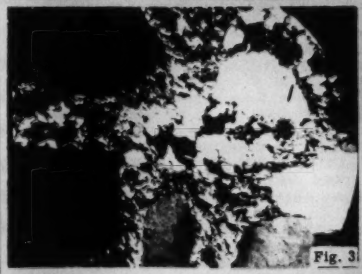
Fig. 3

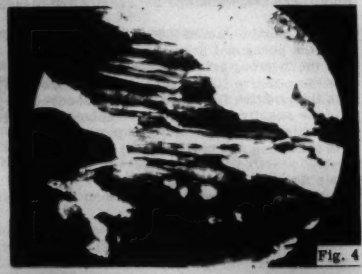
Fig. 4

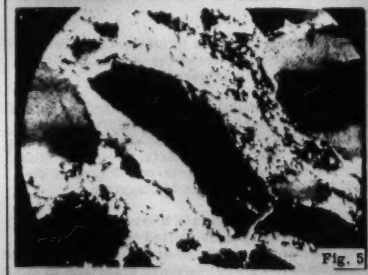
Fig. 5

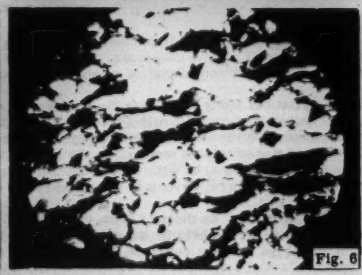
Fig. 6

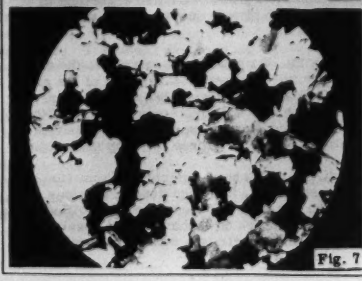
Fig. 7

Figs. 1-7--(1) Undeformed detrital grains with interstitial peripheral-growth quartz; (2, 3) crush-quartz cluster, plane light, and under crossed nicols; (4, 5) incipient formation of needle quartz; (6) needle-quartz fabric produced by fracturing; (7) granoblastic texture characteristic of completely recrystallized quartz

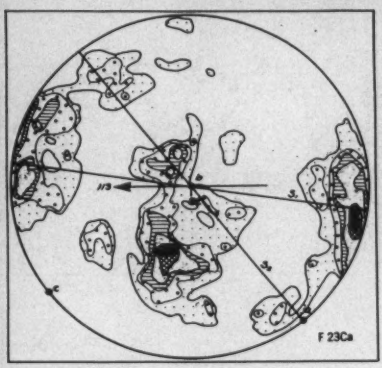

Fig. 8--Partial diagram F 23Ca, Weverton quartzite from South Mountain summit on highway U.S. 40, Maryland (150 small grains, 1-2-3-4-5-6 o/o)

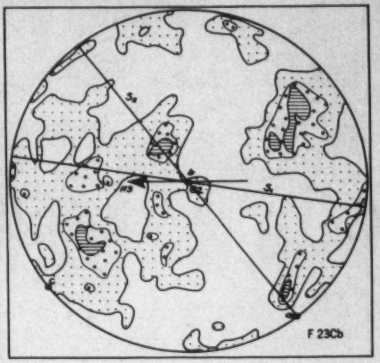

Fig. 9--Partial diagram F 23Cb, same as Figure 8 (300 large grains, 1-2-3 o/o)

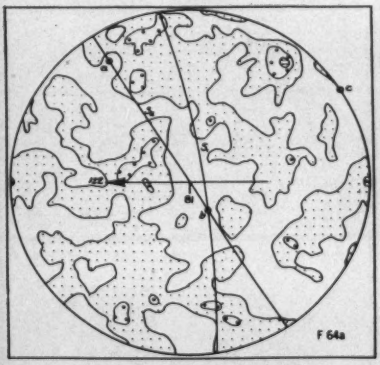

Fig. 10--Partial diagram F 64a, Weverton quartzite from west of Arendtsville, Pennsylvania (300 small grains, 1-2-3 o/o)

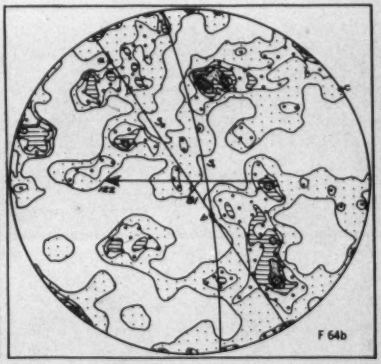

Fig. 11--Partial diagram F 64b, same as Figure 10 (100 large grains, 1-2-3-4-5 o/o)

larger original grains or larger annealed metacrysts" [2]. Figure 1 shows undeformed detrital grains with interstitial peripheral-growth quartz which is also a distinct textural type. The peripheral-growth quartz is generally free from contamination and is restricted in its distribution.

Granulated detrital grains are described as crush quartz. The shattering of grains during movement yields an even-granular mat of equant particles which remain segregated in clusters during the early phases of recrystallization. The original grain-boundary is retained for a time and defines the superindividual. A crush quartz-superindividual is shown in Figures 2 and 3.

Needle quartz is developed by splintering of the grain along glide-planes. The resulting

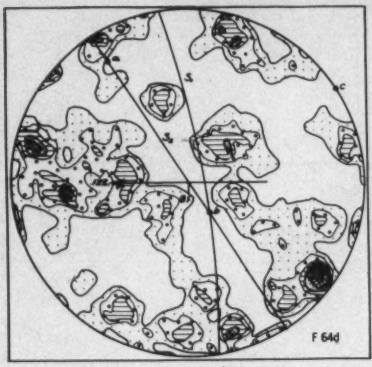

Fig. 12--Partial diagram F 64d, same as Figure 10 (100 quartz needles, 1-2-3-4-5-6 o/o)

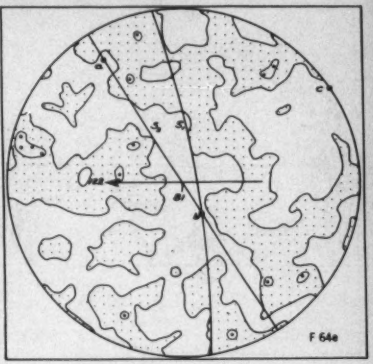

Fig. 13--Composite diagram F 64e, same as Figure 10 (500 undifferentiated quartz, 1-2 o/o)

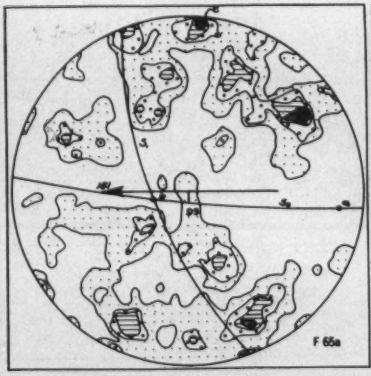

Fig. 14--Partial diagram F 65a, Weverton quartzite from west of Gettysburg, Pennsylvania (200 random elongated quartz, 1-2-3-4-5 o/o)

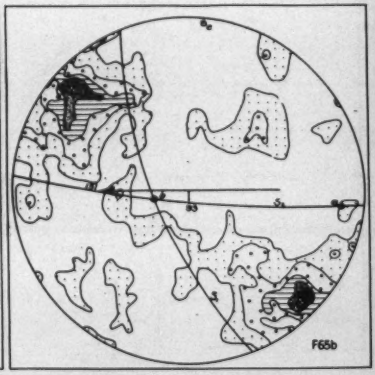

Fig. 15--Partial diagram F 65b, same as Figure 14 (300 parallel elongated grains, 1-2-3-4-5-6 o/o)

lineation is generally well-defined. A grain having numerous active glide-planes will produce thin slivers each having a greater ratio of elongation than the needle quartz formed in a grain having only a few active glide-planes. Figures 3 and 5 show incipient formation of quartz needles; Figure 6 shows needle-quartz fabric

Recrystallized quartz is the last stage in the process of recrystallization. When the particles of a superindividual reach optical homogeneity they coelesce and a single annealed grain results. A recrystallized fabric with granoblastic texture is shown in Figure 7.

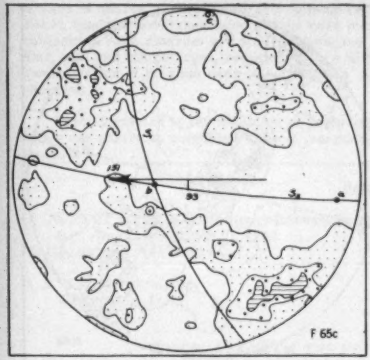

Fig. 15--Composite diagram F 65c, same as Figure 14 (500 undifferentiated grains, 1-2-3 o/o)

Most deformed sedimentary rocks subjected to petrofabric analyses have been only partially recrystallized and hence usually show at least two types of quartz in thin section.

Random measurements of the orientation of quartz-axes in a series of sedimentary rocks showing different degrees of recrystallization will produce vague and uninterpretable diagrams. Analysis of a tectonite, however, will reveal that stage of recrystallization where the majority of grains have a similar lattice-alignment. Selective measurements of only the largely or wholly recrystallized grains would show the preferred orientation, but their significance becomes more highly camouflaged as other grains in earlier stages of the process of recrystallization are measured and plotted in the same diagram. Since the types of recrystallizing quartz can be differentiated it is apparent that partial diagrams resulting from these selective measurements will most clearly reveal the significant data.

The fabric diagrams in Figures 8 to 16 illustrate the variation in patterns developed through selective and non-selective measurements of quartz grains. Diagram F 23Ca (Fig. 8) represents the distribution of axes of 150 small quartz-grains whose maximum concentration is six per cent. Three hundred large grains were measured in one thin section; diagram F 23Cb (Fig. 9) shows a maximum concentration of only three per cent. In this case the interpretable pattern can be obtained from the obvious preferred orientation of small grains, whereas the large grains merely camouflage the trend of recrystallization by their random orientations.

A series of four diagrams was prepared from specimen F 64. Diagram F 64a (Fig. 10) was developed from the measurement of 300 small grains; the largest maximum is three per cent. F 64b (Fig. 11) shows a marked preferred orientation with five per cent maxima developed from measurement of 100 large grains. F 64d (Fig. 12) was developed from measurement of 100 grains of needle quartz; the highest concentration of axes is shown by a six per cent maximum. A composite diagram F 64e (Fig. 13) was made by plotting the axes of 500 undifferentiated grains. The resulting diagram shows a wholly random distribution of axes and gives no hint of the preferred orientation that is clearly revealed by the partial diagrams.

F 65a (Fig. 14) represents the optical orientation of 200 random elongated grains; the diagram shows concentrations of quartz axes up to five per cent. F 65b (Fig. 15) is constructed from optical measurement of 300 parallel elongated grains. Here the concentrations reach six per cent as might be suspected from the close relationship between quartz lattice, glide-planes, and the shape-axes of the needle quartz. F 65c (Fig. 16) is a composite diagram representing the orientation of axes of 500 grains. A maximum of three per cent was the highest obtainable.

Neocrystallized versus detrital quartz--Another common element of confusion in the presentation and interpretation of quartz-fabric diagrams is the lack of distinction between neocrystallized and detrital quartz. In a migmatite, formed by the intrusion of igneous material into rocks of sedimentary origin, the texture is commonly such that it is difficult or impossible to distinguish the introduced quartz from the detrital grains. As recrystallization proceeds the detrital grain slowly loses its identity and becomes indistinguishable from the neocrystallized quartz. The significance of the preferred orientations, either shape or lattice, developed in igneous quartz during the injection of the molten material is only partially understood. Hence, if one plots on a single diagram the orientation of the axes of all quartz grains in a thin section of a migmatite, an additional element of confusion, if not actual error, is introduced.

When it is realized that such a rock may show two or more types of recrystallizing quartz besides the neocrystallized material the complexities become multiplied to the point where discrimination in measurements is essential to the production of an interpretable diagram.

Composite diagrams--Although partial diagrams are necessary to the understanding of most

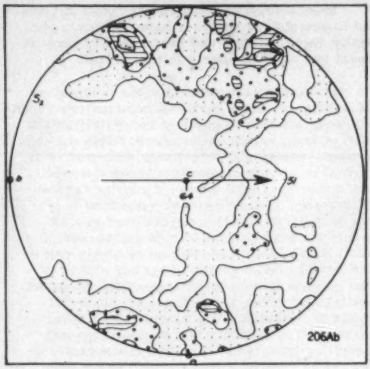

Fig. 17--Composite diagram 206Ab, Wissahickon schist from near Florence, Maryland (300 grains, 1-2-3-4 o/o)

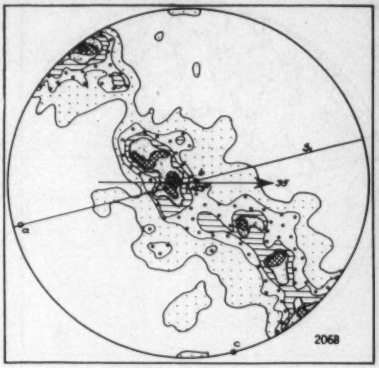

Fig. 18--Composite diagram 206B, same as Figure 17 (300 grains, 1-2-3-4-5-6 o/o)

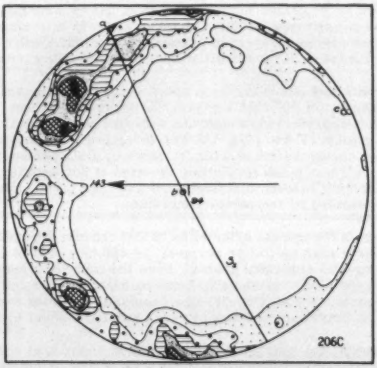

Fig. 19--Composite diagram 206C, same as Figure 17 (300 grains, 1-2-3-4-5-6 o/o)

quartz-rich fabrics, the importance of composite diagrams should not be discounted. Composite diagrams are valuable to indicate the degree of deformation or recrystallization of a rock in relation to other rocks in an area under study. Even this application is restricted since many deformed rocks are not tectonites, and hence have no preferred directional element that can be used as a basis for comparison. Only in the advanced stages of recrystallization do the grains become unified in type and orientation to the extent that random measurements will produce an interpretable diagram. Such a diagram is in essence still a partial diagram since it has been developed largely from measurements of axes of one type of quartz.

Diagrams 206Ab, 206B, and 206C in Figures 17 to 19 were prepared from three mutually perpendicular cuts from a specimen of quartz schist. They show the results of random measurements

of axes of quartz grains whose orientations have become unified through complete recrystallization. Three hundred undifferentiated grains were measured in each thin section. The girdles and maxima obtained in each diagram are well-defined; the largest concentrations of axes in the diagrams are four, six, and six per cent, respectively. A distinct ac girdle is apparent in each diagram with a concentration of maxima near 'a'. (Note: 'a' and 'b' in diagram 206B [Fig. 18] should be interchanged).

Discrimination in the selection of grain-types will allow the production of partial diagrams which can easily be combined to form composite diagrams, whereas the reverse procedure is impossible.

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OBSERVATIONS ON THE FORMATION OF SURFACES OF SLIP IN MILD STEEL, IN METALS, AND IN NATURAL ROCKS

A. Nadai

(Abstract)

The mechanical conditions under which solids can deform permanently without fracturing are of interest to engineers, metallurgists, and, in some applications, to geologists. The ductile metals are the most widely used artificial materials of construction. It is natural, therefore, that their mechanical properties have been widely investigated by engineers and metallurgists. Among these metals soft steel shows the peculiarity that when it is deformed to a small degree fine markings of an astonishingly regular pattern appear on the surface of the deformed test-piece. These fine patterns frequently accompany the first plastic deformations after the yield-point has been reached in steel. They are traces of thin layers in which the metal has been deformed locally. The description and geometry of these surfaces of slip has opened up broad theoretical approaches to a mechanics of the plastic states of stress in steel. In minerals and in rocks, on the other hand, many evidences of permanent deformation are known to the geologist. A description of the plastic distortion observable in the strata of rocks is one of the fundamental problems of geology. The conditions encountered in the deeper sedimentary or igneous rocks--the prevailing of small differences of stress, of elevated temperatures increasing with the depth, of high average pressures--are important factors contributing to plastic flow. Changes in the structure of rocks are known which are frequently very similar to those which have been observed in plastically deformed metals. A number of observations of this kind were shown in examples of which a large number have not been yet reported in publications. The flow-patterns were demonstrated in the following examples: Compression of prismatic steel pieces; compression of paraffin cylinders; flow-lines starting near a small hole in bodies deformed by compression; a case of this type in meteoric iron. In an extruded tube of clay beautiful markings were discovered through an accidental fracture of the tube, disclosing the flow-pattern in the tube wall which had been influenced through the friction along the tube surface. Square and rectangular plates were deformed by means of a concentrated load while the plates were resting along their circumference. Again beautiful very regular flow-patterns appeared on the surface of these plates. If a steel block, the surface of which has been polished, is deformed by a concentrated pressure, for example, if the pressure is exerted by means of a cylindrical punch, beautiful slip-lines appear around the impression consisting of two systems of logarithmic spirals. Reference was made to observations in Japan in which it was claimed that the secondary cones on one of the volcanoes in Japan appear to be distributed along similar logarithmic spirals which would indicate a radial symmetry of the stress-field. In a motion-picture film several examples of the propagation of the plastic zone and of the formation of surfaces of slip were demonstrated in tension-tests and in bending tests with plates.

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SECONDARY STRUCTURES OF THE MARTINSBURG SLATE, NEW JERSEY

John G. Broughton

(Abstract)

The progressive development of fracture-cleavage can be traced in the Martinsburg slate of Warren County, New Jersey. Over much of the area, the structures are similar to those described by BEHRE in "Slate in Pennsylvania". These serve as a standard of comparison for the aberrant structural elements elsewhere in the area. The folded slate is overturned to the northwest; fold-axes pitch gently to the northeast. The axial planes of these folds are paralleled by well-developed flow-cleavage along which shear folding has taken place. Field and microscopic evidence indicate that stretching in "a" has accompanied development of the flow-cleavage. The typical tectonite orientation shows Maximum I of SANDER.

South of Delaware, New Jersey, the flow-cleavage has been folded and the bedding refolded. Fracture-cleavage has formed parallel to the axial planes of flow-cleavage folds. This cleavage develops uniformly from north to south until its field appearance is almost identical to that of flow-cleavage. Microscopic and petrofabric study shows that the original orientation in "a" has been partially destroyed and that a new orientation related to the fracture-cleavage has developed.

The formation of fracture-cleavage in this locality is ascribed by the author to major overthrusting of pre-Cambrian and Cambro-Ordovician rocks over the Martinsburg formation. This conclusion is based on (1) the northwestward extension of fracture-cleavage opposite the point of furthest advance of the overthrust, (2) the gradual increase in intensity of deformation toward the fault, and (3) the fact that the cleavage-dip progressively flattens (as a result of antithetic rotation) from north to south.

It is believed that flow-cleavage may develop by extreme shearing along fracture-cleavage planes.

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CORRELATION OF LINEATION WITH ROCK-MOVEMENT

Ernst Cloos

(Summary)

"Lineation" is a collective term for any kind of linear structure in or on a rock. It is meant to be descriptive and non-genetic. Lineations are striae on slickensides, fold-axes, flow-lines, stretching, elongate pebbles or oolites, wrinkles, streaks, intersections of planes, linear parallelism of minerals or components, or any other kind of linear structure of megascopic, microscopic, or regional dimensions.

Linear structures are indicators of the direction of movement and thus much used as reference-directions of deformation, folding, flowage, gliding, slippage, shearing, orientation of tectonic units, and are important as means of orienting coordinates in fabric analysis.

Inasmuch as almost all fabric analyses are linked with tectonic movements and field-orientation through the use of lineations as reference-direction, it becomes necessary to look into this reference-direction, its use, and formation. A certain amount of simplification has obscured the situation and it has been said, for instance, that lineation is always perpendicular to the direction of movement, or that the lineation is in the direction of fold-axes. Linear structures are neither always perpendicular nor always parallel to the direction of movement. The purpose of the paper is to show the different kinds of lineation observed and their orientation with reference to rock-movements.

Two directions are generally well recognized, namely, lineation parallel and lineation normal to the direction of movement. The direction of movement is either the principal direction of propagation as in the flow of a valley glacier parallel to the direction of the valley, or it is a secondary direction normal to the principal direction as in the movement within the front of a glacier and normal to the valley axis. In correlating lineations with movement-directions a clear definition of these directions is as essential as the distinction between types of lineations.

It has become customary to refer movements to coordinates a, b, and c. b is the direction of the fold-axis, a is normal to it and within the direction of transport, and c is normal to the plane of a and b. Lineations are therefore most commonly either parallel a or b.

Figure 1 shows the different possibilities which are recognized in the literature and their orientations with respect to the coordinate system. It is obvious that an adequate description and clear definition should accompany every description of linear structures if confusion and needless controversy are to be avoided.

The first paper on lineation is by C. F. NAUMANN in 1839 "On the linear parallelism or stretching of rocks". Since then 230 geologists have mentioned, described, or discussed lineation. It has been plotted in 73 printed geological maps. There are 287 papers containing information on kind or orientation of linear structures, or both. Generally, information is meager, insufficient, and frequently inaccurate or incomplete.

Parallel primary igneous flow (see Fig. 1) has been observed first by DE LA BECHE in 1851 and by 49 later authors. Primary igneous flow normal to the direction of principal movement was

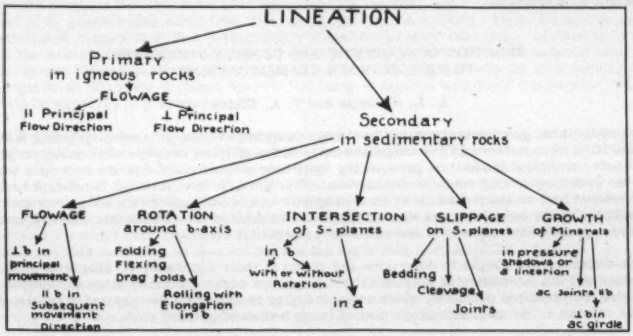

Fig. 1--Different possibilities recognized in the literature and orientations with respect to the coordinate systems

first noticed by ALBERT HEIM in 1878 and by 21 authors. Secondary flow normal b has been described by ALBERT HEIM in 1878 and by 53 subsequent workers; parallel secondary flow was noticed by DE LA BECHE in 1858 and by 59 authors after him. Rotation around b is described in NAUMANN'S text in 1858 and has then been described by 52 authors. S. HOUGHTON noticed lineation due to intersection of planes in 1856 and there are 36 papers with similar descriptions after him. Slippage normal to b in the bedding planes has probably been described first by ALBERT HEIM in 1878 and I have found only ten papers with similar descriptions. Slippage on cleavage is also first mentioned by HEIM. Slippage-traces on faults are very frequently described and have not been included in the present count. The first to describe growth of minerals seems to be LORETZ in 1882. This type of lineation has not been observed frequently.

Whilst the above count may not have reached all papers, it shows, however, that lineation has received some attention for over 100 years and that the possibilities are rather numerous. A complete paper containing bibliography and short abstracts of papers will be published in the near future.

The following conclusions have been drawn:

Lineation is not simply normal to movement and cannot be assumed to be b without careful investigation and subsequent precise definition. "Lineation" alone without a more complete description may mean one of 15 different things.

Folds are not necessarily perpendicular to movement; small folds and wrinkles can very well be in the direction of movement.

Girdles in fabric diagrams need not be indicative of the direction of movement. This can be parallel to the girdle-axis or parallel to the fold-axes.

Movement and stretching parallel b is limited by the amount of arcuation in the area (orogen, glacier, plutonic dome); movements in a are unlimited.

Many of the so-called stretched conglomerates parallel to b are not stretched but due to intersection of shear-planes and rotation of beds.

Lineation is one of the most significant and important structures and should appear in all complete structure or other geologic maps where it can be observed and measured. In addition to a symbol for lineation, there should also be a figure indicating its pitch.

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RELATION OF MAGNETIC AND DENSITY CONTRASTS TO IGNEOUS-ROCK CLASSIFICATIONS

L. L. Nettleton and T. A. Elkins

In recent years, gravimeter surveys have been extended over large areas, including many which also have been covered by the magnetometer. Maps of these surveys show many large and more or less coincident anomalies, presumably indicating magnetic and density contrasts within the igneous basement having common boundaries. Therefore, it is of interest to attempt to determine by independent means the association of magnetic and density contrasts and to see whether the magnitudes of the coinciding gravity and magnetic anomalies are reasonable expressions of two different geophysical aspects of the same body of igneous rock.

Rock-densities are simple to determine and direct in their significance. Magnetic-susceptibility values and the intensities of magnetization of igneous rocks are much more difficult to evaluate, so that the principal questions which arise in trying to associate density and magnetic contrasts are related to the magnetic properties of large bodies of igneous rock.

Magnetite is by far the most common and most highly magnetic mineral, so that it seems reasonable to assume that the magnetic properties of igneous rocks are controlled largely or almost entirely by their magnetite content. Therefore, we will consider that a magnetizable rock is composed of individual particles of magnetite disseminated through a non-magnetic matrix. If, as is usually the case, the magnetite proportion is small, the individual magnetite particles are separated from one another by distances large compared with their dimensions.

To the extent that the individual particle can be approximated by an ellipsoid, the magnetization I_1 of a single such particle will be determined by the applied field H_e, by the susceptibility of the material, k_0, and also, to a very great degree, by the demagnetization factor, λ, as shown [see 2 of "References" at end of paper] by the relation

$$I_1 = [(k_0/H_e)/(1 + k_0\lambda)]$$

If a rock has a volume-fraction, P, of magnetite, the magnetization of the rock as a whole (ignoring the demagnetization effect for the rock as a whole, but in this case, where the effective susceptibility is low, this is not a very important factor, as is indicated by Table 1) will be

$$I = PI_1$$

Then the effective susceptibility, k, of the rock as a whole will be

$$k = (I/H_e) = (PI_1/H_e) = [Pk_0/(1 + k_0\lambda)] = Pk'$$

where $k' = [k_0/(1 + k_0\lambda)]$.

It is evident that if we knew the volume-percentage of magnetite in a rock together with some

way to evaluate λ and thereby k', we could calculate the effective susceptibility.

The demagnetization-factor depends upon the geometry of the particles and can be calculated for certain geometric forms. If the particles are spherical, λ has the value (4 /3).

GRENET [3] apparently was the first to consider carefully the geometric and demagnetization-factors and to point out that, for disseminated magnetite in rocks, the effective susceptibility (k') is only slightly dependent on the susceptibility of the magnetite itself (that is, on k_0). GRENET gives a table of this relation for spherical particles which (slightly extended) is given here as Table 1.

If the particles are not spherical in form but are elongated, the value of k' will be larger than the above figures if the magnetization is in the direction of the long axis and less if in the direction of the short axis. For instance, GRENET calculates that for an ellipsoid of revolution with a ratio of long to short axes of ten, the value of k' is 2.08 (for $k_0 = 10$) for magnetization along the long axis, and 0.156 for magnetization along the short axis. For the same ellipsoid, the mean value of k' for the three axes is 0.797.

It should be noted that the value of k' approaches a constant and is not substantially increased for values of k_0 greater than about five, even as k_0 approaches infinity. Thus, for a rock containing disseminated magnetite with a susceptibility somewhat greater than unity, we should be able to calculate the susceptibility of the rock as $P \times k'$, with k' having a value in the neighborhood of 0.2 or a little larger. If the particles are elongated and oriented parallel with the magnetizing field or are aggregated so that their distance apart is not large compared with their dimensions, the value of k' would be expected to increase.

SLICHTER [4], in the early days of magnetic prospecting, made measurements of the susceptibility of rocks and of artificial mixtures of sand and magnetite. Figure 1 from SLICHTER'S paper shows the effective susceptibility as the percentage of magnetic material decreases. The ordinates correspond to values of k'. Toward the right-hand side of this Figure the susceptibility for the mixture containing magnetite approaches a value of about 0.25 and the mixture made with powdered iron also approaches almost as low a figure. This is just what would be expected from Table 1, as the conditions on which this Table are based are approached as the portion of magnetic material is decreased, and this condition is reached toward the right side of SLICHTER'S figure.

An experimental determination of k' can be made in any case where the susceptibility of a rock and its volume-percentage of magnetite have been determined. A search of the literature reveals a few examples of data of this kind which are assembled in Figure 2.

SLICHTER'S paper mentions two samples of gabbro for which the susceptibility was measured and the magnetite determined by crushing the sample and separating with a magnetic separator.

Two Japanese, KATO [5] and NAGATA [6], determined susceptibilities of lavas from around volcanoes in Japan and estimated the magnetite content from chemical analysis of these rocks by

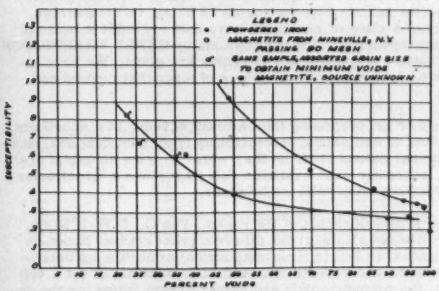

Fig. 1--Specific susceptibility of powdered magnetite and powdered iron in various concentrations in a non-magnetic matrix (after Slichter)

Table 1--Relation between mineral susceptibility (k_0) and effective susceptibility of rock (k') for disseminated spherical particles

k_0	k'
0.01	0.0096
0.1	0.0705
1	0.193
5	0.228
10	0.233
100	0.238
∞	0.239

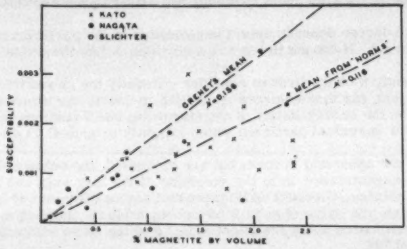

Fig. 2--Measured susceptibilities in cgs units of rocks with various magnetite content (points by Kato and Nagata from individual samples, with magnetite determined by "norms" from chemical analysis; points by Slichter from individual samples, with magnetite determined by magnetic separator; "Grenet's mean", average ratio of susceptibility from 86 samples, with magnetite determined by thin sections; "Mean from norms", average ratio of susceptibility to magnetite for all Japanese samples)

"recasting" the analysis into the "normative" magnetite. The average k' thus determined is 0.116 and the maximum value is 0.23.

GRENET determined susceptibility of rocks and then examined thin sections under the microscope, measured the area of dark minerals and then, assuming these dark minerals to be magnetite, computed the percentage of magnetite in the rock. From 86 samples, the average value of k' thus obtained is 0.156, as indicated on the Figure, and with a maximum value of 0.34.

The chemical analysis and thin-section measurements both would be expected to give too large values of magnetite and, therefore, too small values of k' because the chemical analyses would throw some iron radicals into magnetite, whereas they may have come from non-magnetic minerals containing iron, and GRENET'S count of dark minerals would include some which are not actually magnetite. Therefore, the maximum values of Figure 2 are the ones which, presumably, would approach the most correct evaluation of the relationship of susceptibility to magnetite, and it is evident that these maximum values are in the neighborhood of those expected from theory.

The data assembled on Figure 2 include all the useful material brought out by a rather complete search of the literature. The wide scatter of values is not very encouraging but suggests a basis for another step. To the extent that the average k' value determined from the Japanese work is valid, it may be used for deriving values of susceptibility from other chemical analyses, and thus opens the way to make some use of a vast body of data on the chemical analyses of igneous rocks. There are available many analyses for which the minerals of the "norm" and the densities are both given. If we accept the magnetite indicated by the norms as being, on the average, proportional of the actual magnetite content of a class of rocks, we have thus available a basis of estimating magnetite content and thereby susceptibility. The publications by HENRY WASHINGTON list a total of 1,450 analyses for which normative magnetite and densities are given. We have attempted a statistical analysis of these data to determine typical values of magnetite content and density.

It should be clearly understood that we are not proposing this indirect scheme as a substitute for direct measurement of samples. The idea of estimating susceptibility from chemical analyses is quite parallel with that of estimating mineral content (that is, the "norm") from chemical analyses. In both cases a value is determined indirectly from available data to replace a direct determination (of susceptibility or "mode") which has not or will not be made.

There immediately arises the question of classification of the rocks. The C.I.P.W. (CROSS, IDDINGS, PIRSSON, WASHINGTON) system divided all the rocks into five great classes based on the relative proportions of Salic (silica-alumina) to Femic (iron-magnesian) minerals, as determined by chemical analysis. Figure 3 shows the end-results of a statistical analysis of the 1,450 samples [7]. From a statistical standpoint, the magnetite data are rather disappointing, as the deviations are great (see bottom row) and there is considerable overlapping from one class into another. For this reason, medians rather than averages are used as they are statistically preferable under such circumstances. From the magnetite percentages as given in the third row of

Figure 3, the intensity of magnetization in the Earth's field (0.6 oersted) was calculated, using for k' the value 0.116 determined from the average of the Japanese measurements, since they are also based on the magnetite "norms" from chemical analyses.

If we assume that igneous rocks are stratified according to density, it seems reasonable to assume that normally the more basic rocks (that is, those with higher class-numbers) would be deeper, as the density progresses rather regularly throughout the classification (as would be expected from its chemical basis). Therefore, we might presume that upward deformation within large igneous-rock bodies would involve intrusion of the presumably deeper and higher numbered classes into lower numbered (and presumably overlying) classes. The contrasts which would result from such deformation are indicated by the upper right-hand half of Figure 4 (contrasts from down-warps of upper and lighter into lower and heavier strata are indicated by the lower-left half of Figure 4).

Figure 5 indicates some magnetic contrasts derived from the analysis of anomalies on maps of magnetometric surveys. A considerable proportion of the contrasts thus derived are in the general range of those calculated and shown in Figure 4. The rather extreme cases may be considered as non-typical concentrations of magnetite. On the whole, the comparison indicates that the statistical work has led to reasonable values for contrasts of magnetization. The values of density are of a reasonable order of magnitude from general experience with gravity surveys, but a direct evaluation of such contrasts from surveys is not possible without additional information to fix the size or boundaries of the rock-masses involved.

C.I.P.W. CLASSIFICATION

CLASS		I	II	III	IV	V
NUMBER OF VALUES		502	583	283	82	20
MEDIAN	% MAGNETITE BY WT.	1.39	3.94	5.34	4.87	4.98
	DENSITY	2.63	2.78	2.98	3.12	3.30
CALC. I-PAH ($K \times 10^6$)	$K = 0.116$	500	1470	2140	2080	2220
MEAN DEVIATION	MAGNETITE	1.03	2.09	2.87	3.29	4.88
	DENSITY	.007	.010	.008	.018	.026

Fig. 3--Statistics for density and magnetite content of igneous rocks ("per cent magnetite by wt.", median value of per cent by mass of normative magnetite as given in Henry Washington's tables of chemical analyses of igneous rocks) [Chemical analyses of igneous rocks, U.S.G.S. Prof. Paper 99 (1917), and The superior analyses of igneous rocks from Roth's Tabellen, U.S.G.S. Prof. Paper 28 (1904)]

CALCULATED MAGNETIC AND DENSITY-CONTRASTS

INTRUDED CLASS			INTRUSIVE CLASS I	II	III	IV	V
I	M			+970	+1840	+1580	+1720
	D			+013	+033	+049	+087
II	M	-970			+870	+590	+750
	D	-013			+020	+038	+034
III	M	-1840	-870			-80	+80
	D	-033	-020			+018	+034
IV	M	-1580	-590	+80			+180
	D	-049	-038	-018			+018
V	M	-1720	-750	-80	-160		
	D	-087	-054	-034	-018		

Fig. 4--Density and magnetization contrasts between classes of igneous rocks (C.I.P.W. Classification), based on median values of Figure 3 (densities are in grams/cc, magnetization-values are in cgs units $\times 10^{-6}$)

CONTRASTS FROM MAGNETIC SURVEYS

LOCATION	NO OF ANOMALIES	AVERAGE CONTRAST
EWYO	3	300
EWYO	3	1040
EWYO	1	2500
W TEX	4	820
W TEX	6	840
W TEX	3	1700
CROSBYTON HIGH	1	6700
MISS	4	1430
MISS	6	1530
MISS	1	4120
CENTRAL AMERICA	1	900

Fig. 5--Magnetization-contrasts (in cgs units $\times 10^{-6}$) within igneous rocks, estimated from anomalies on maps of commercial magnetic surveys (estimates calculated by James Affleck at Gulf Research Laboratory, to whom grateful acknowledgment is hereby made)

The fact that the magnetic and density contrasts of Figure 4 in most cases have the same sign suggests that we would normally expect coinciding magnetic and gravity anomalies to have the same sign; that is, gravity highs and magnetic highs should go together, as should gravity lows and magnetic lows. In only one case (intrusion of Class IV into Class III) are the signs opposite, and in that case the magnetization contrast is small. The wide range of the ratio of magnetic to density contrasts which is indicated by the calculated contrasts of Figure 4 suggests that the relative magnitudes of gravity and magnetic anomalies may range over rather wide limits.

The final results of this work are: (1) A definite basis exists for the determination of susceptibility and intensity of magnetization of rocks from their magnetite content; (2) the possibility of determining magnetite content from chemical analysis opens a possibility of access to a large volume of new data on magnetic susceptibilities and magnetization contrasts; (3) a reasonable range of probable magnetic and density contrasts within basement-rocks has been established; (4) a certain amount of association of magnetite content with density comes about through their mutual association with the chemistry of igneous rocks. Finally, we hope that this work may promote a better appreciation of the expected association of magnetic and gravity contrasts so that more consideration of these factors may lead to a better evaluation of areas where both gravity and magnetic surveys are available.

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Pittsburgh, Pennsylvania

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AMERICAN GEOPHYSICAL UNION

TWENTY-FIFTH ANNUAL MEETING

PART V

SECTION OF HYDROLOGY

REPORTS

Washington, D. C.

June 1 and 2, 1944

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REPORTS, PERMANENT RESEARCH-COMMITTEES

SECTION OF HYDROLOGY

WASHINGTON MEETING, JUNE 1 and 2, 1944

REPORT OF COMMITTEE ON PRECIPITATION, 1943-44

Merrill Bernard, Chairman

Carlos Cabral
A. R. Codd
Leonard B. Corwin
Glen N. Cox
Robert W. Gay
W. G. Hoyt
J. W. Howe
Charles R. Hursh
J. Otis Laws
Luna Leopold
F. T. Mavis
A. K. Showalter
Waldo E. Smith
C. W. Thornthwaite

Military assignments, war-imposed additional duties, and the inevitable shifts of interest during time of war, have dictated the curtailments in this Committee Report.

Primary interest continues in the network of recording precipitation-stations operated by the Weather Bureau in cooperation with the Corps of Engineers and financed from Flood Control funds provided by the latter agency. The network continues to operate approximately 2,500 recording gages. Approximately 100 non-recording stations have been added to the climatological network of the Weather Bureau, sustaining the total of about 8,000 precipitation-stations in all.

The utilization of hydroclimatic stations to provide synoptic reports of excessive rains for the purpose of flood-forecasting, both by the operational offices of the Corps of Engineers and the river forecasting-centers of the Weather Bureau, has expanded from 7 to 14 networks during the year. The number of reporting stations has increased from 193 to 502.

A. R. CODD -- In general, the Northwestern States, Wyoming, Montana, Idaho, Oregon, and Washington, enjoyed a rather good season during 1943. Precipitation was slightly below normal as far as State averages are concerned. High-elevation stations showed above-normal precipitation which produced an exceptionally good water-year.

The maintenance of the Cooperative Hydroclimatic network of recording precipitation-stations as well as the regular climatological stations has been a trying problem during this National emergency. A number of gages have had to be shifted from observer to observer in the same locality, but relatively few stations have been definitely closed. The high-elevation stations are perhaps the most difficult to maintain. The network as a whole has remained intact and the class of records from the individual stations has improved materially, due primarily to regular systematic inspection and instruction.

GLEN N. COX -- There has been little change in the work carried on by the Weather Bureau in precipitation-observations in the Lower Mississippi and West Gulf States. The area covered includes all of the States of Arkansas, Oklahoma, and Texas, and a portion of the States of Colorado, Kansas, Kentucky, Louisiana, Mississippi, Missouri, New Mexico, and Tennessee. Additional recording rainfall-stations are gradually being added to this network.

A number of field-installations under the supervision of the Soil Conservation Service have been placed under the direct supervision of the Weather Bureau, thus insuring a continuation of important records while freeing the Soil Conservation Service of the responsibility of caring for and operating the precipitation-stations.

In addition to the Corps of Engineers, a number of agencies cooperate to furnish the data reported in the Hydrologic Bulletin, such as the Air Corps Weather Service, Bureau of Plant Industry, Civil Aeronautics Authority Airway Communication Station, Louisiana State University, Soil Conservation Service, United States Coast Guard, and the United States Lighthouse Service.

J. W. HOWE -- Table 1 shows the distribution of gages and the growth of the Weather Bureau-Corps of Engineers network in the upper Mississippi Valley since its inception. The figures do not include the long-established cooperative stations of the Weather Bureau. Approximately 60 per cent of the gages are recording.

Table 1

State	Year of installation				Total No. gages	Per cent recording gages
	1940	1941	1942	1943		
Iowa	19	7	1	1	28	93
Michigan	4	5	12	3	24	75
Minnesota	72	39	17	5	133	44
Missouri	10	3	0	1	14	78
North Dakota	12	3	1	0	16	44
Wisconsin	42	29	3	3	77	74
Total or average	159	86	34	13	292	61

Observation of rainfall and runoff on the Rapid Creek Watershed, a basin of 24.5 square miles near Iowa City, is now on a permanent basis. Cooperation of the United States Weather Bureau, the United States Geological Survey, and the United States Engineer Corps, with the Iowa Institute of Hydraulic Research has made possible the retention of paid observers. Four recording rain-gages, two recording ground-water gages and a stage-recorder at the discharge-control are in continuous operation. The United States Geological Survey generously consented to operate one of the rain-gages near its surface-water control.

Ralston Creek Watershed (three square miles) near Iowa City has not been under continuous observation since 1924. Records of rainfall, runoff, and ground-water have, so far, been continued despite war-time difficulties. Five recording rain-gages have been operating on Ralston Creek since 1941.

A. K. SHOWALTER -- The Hydrometeorological Section, in cooperation with the Engineer Department, Corps of Engineers, is continuing its researches into excessive precipitation.

Publication, through the facilities of the Engineer Office at Vicksburg, of larger editions of completed reports has continued. Four such reports on maximum possible precipitation over designated areas are now available. Numbered 1 to 4, they deal with the Ompompanoosuc Basin above Union Village, Vermont, the Ohio River above Pittsburgh, the Sacramento Basin of California, and the Panama Canal Basin. For military reasons, the circulation of the last mentioned is severely restricted.

A paper on the application of the techniques used in these reports to forecasting of quantitative precipitation was presented by A. K. SHOWALTER before a New York meeting of the American Meteorological Society in January. Mr. SHOWALTER also presented a simplified method for the computation of the rate of rainfall in the January 1944 issue of the Monthly Weather Review. The Section's report on thunder-storm rainfall in the United States is nearing completion. It will include a pertinent section on the reliability of rain-gage networks.

Important recent storms have been given special treatment by publishing all storm-rainfall data. Already published are the supplements for the storms of May 19-23, 1942 (Pennsylvania), June 14-18, 1942 (New York and New England), July 17-18, 1942 (Wisconsin). Nearing completion are the supplements for the Potomac storm of October 11-17, 1942, and the widespread storms of December 27-31, 1942, March 10-22, 1943, and May 10-22, 1943.

Further development and improvement of the shielded storage-snow-gage of the Alter type is continuing at Soda Springs, California, under the guidance of J. E. CHURCH and R. W. GERDEL. Recording gages of the Stevens type are also under observation at Soda Springs.

The continuing investigations on the influence of falling rain on subsequent runoff from paved and sodded areas by the Department of Public Roads under CARL IZZARD, represents a substantial contribution to hydrologic knowledge acquired during the current year.

U. S. Weather Bureau,
Washington, D. C.

REPORT OF COMMITTEE ON GLACIERS, 1943-44

François E. Matthes, Chairman

(Published with the approval of the Director of the United States Geological Survey)

The personnel of the Committee is now as follows:

François E. Matthes (Chairman), Senior Geologist, United States Geological Survey, Washington, D. C.
William H. Hobbs, Professor Emeritus of Geology, University of Michigan, Ann Arbor, Michigan
Colonel Lawrence Martin, Chief, Division of Maps, Library of Congress, Washington, D. C.
James E. Church, President, International Commission of Snow and Glaciers, Agricultural Experiment Station, University of Nevada, Reno, Nevada
Captain William Osgood Field, Jr., home address 18 West Twelfth Street, New York, New York
Oliver Kehrlein, Chairman, Committee on Glacier Studies, Sierra Club, 1050 Mills Tower, San Francisco, California
Kenneth N. Phillips, Associate Hydraulic Engineer, Water Resources Branch, United States Geological Survey, Chairman, Research Committee of the Mazamas, 606 Post-Office Building, Portland, Oregon
William S. Cooper, Professor of Botany, University of Minnesota, Minneapolis, Minnesota
Lieutenant Colonel Gerald Fitzgerald, Army Air Force, Headquarters Office, Washington, D. C.
Laurence M. Gould, Professor of Geology, Carleton College, Northfield, Minnesota
Arthur Johnson, Hydraulic Engineer, Conservation Branch, United States Geological Survey, 1105 Washington Building, Tacoma, Washington
Major Weldon F. Heald, 3126 Rubio Canyon Road, Altadena, California
Howard R. Stagner, Park Naturalist, Mount Rainier National Park, Longmire, Washington

The two last named are new members. Major HEALD is one of the few mountaineers in this country who have first-hand acquaintance with the glaciers in the little-known part of the Cascade Range extending from Lake Chelan to the Canadian Boundary. He is equally familiar with the glaciers of Mount Baker, Mount Shukshan, and Mount Olympus, likewise with the glaciers of the Swiss Alps, and he has a broad fund of information on all the glacier-bearing mountains of Europe and Asia. At present he is engaged in special climatologic researches for the Quartermaster General's Corps.

Mr. STAGNER, who comes to the Committee as the accredited representative of the National Park Service, has inaugurated a program of intensive studies on the changes that are taking place in the glaciers of Mount Rainier, not only from one year to the next, but from season to season. These repetitive measurements at short intervals are the first of their kind to be made in this country and doubtless will serve to give us a truer insight into the annual regimen of glaciers--their hydrologic economy.

It is with deep sorrow that the Committee announces the death of its oldest member, who was beloved and esteemed by all, and justly regarded as the dean of American glaciologists--Doctor HARRY FIELDING REID, Professor Emeritus of Dynamical Geology at Johns Hopkins University. He passed away at his home in Baltimore on June 13, 1944, at the age of 85 years. The news of his death reached the Chairman of this Committee just as this report was being transmitted for publication. Only a brief account of his career, therefore, can here be inserted.

Outstanding among REID'S glacial researches are those on the Muir Glacier and the Glacier Bay region, in southeastern Alaska. On his first expedition with a small party of scientists, in 1890, he made a plane-table map of the Muir Glacier and its tributaries, and on his second expedition, in 1892, he added many important details, geographic, geologic, and glaciologic. A number of glaciers, fiords, and peaks about Glacier Bay were named by him. The United States Geographic Board has honored him by naming the principal fiord at the head of the Bay for him.

REID was the first American glaciologist to take a special interest in the study of the secular variations of glaciers and to see the need of their being systematically recorded from year to year. When, therefore, the International Glacier Commission was created by the International Geological Congress held at Zürich, in 1894, he very appropriately was named as representative of the United States on that Commission. He served as its President from 1903 to 1906 and maintained his membership until 1936, when he resigned, suggesting as his successor the present Chairman of the Committee on Glaciers of the American Geophysical Union. During his most active period, from 1895 to 1916, he published no less than 20 successive reports on the variations of glaciers, chiefly

in the Journal of Geology and the Zeitschrift für Gletscherkunde.

Being a physicist and a mathematician as well as a geologist, REID was unusually well qualified to deal with the complex problems of glacier mechanics. In 1896 and 1897 he made systematic measurements on stakes set in the Forno Glacier, in the European Alps, and thus determined the horizontal and vertical movements of the ice in different parts of that glacier. The results obtained furnished him the basis for his conception of the internal structure of a glacier and the progressive deformation which the ice-strata undergo as a result of differential movements -- a conception that has been widely accepted by glaciologists. REID, it need hardly be added, was well known to European students of glaciers; he was an Honorary member of the Société Helvétique des Sciences Naturelles.

REID was also noted for his researches in the fields of geophysics and seismology. He served on the California Earthquake Investigation Commission, in 1906, and contributed Volume II of the Reports of that Commission. He was President of the Seismological Society of America from 1912 to 1914, and President of the American Geophysical Union from 1924 to 1926. The National Academy of Sciences honored him by electing him to its membership, and in addition he was a member of the American Philosophical Society, the Washington Academy of Sciences, and the American Physical Society; fellow of the Geological Society of America; and corresponding member of the Philadelphia Academy of Sciences. He represented the United States on the International Seismological Association.

Among the glaciological studies published by REID the following deserve special mention:

Studies of Muir Glacier, Nation. Geog. Mag., vol. 4, pp. 19-55, 1892.
Report of an expedition to the Muir Glacier, Alaska, U. S. Coast Geodetic Surv. Rep., Part 2, 1891.
Glacier Bay and its glaciers, U. S. Geol. Surv., 16th Ann. Rep., Part 1, 1896.
De la progression des glaciers, leur stratification et leur veines bleues, 8th Internat. Geol. Cong. Paris, 1900, Comptes Rendus, pp. 749-755, 1901.
The reservoir lag in glacier variations, 8th Internat. Geog. Cong. Rep., pp. 487-491, 1905.
The flow of glaciers and their stratification, Appalachia, vol. 11, pp. 1-6, 1905.
The glaciers of Mount Hood and Mount Adams, Mazama, vol. 2, pp. 195-200, 1905.

Glaciers of Glacier National Park, Montana

From the report submitted by Superintendent D. S. LIBBEY it appears that snowfall during the winter 1942-43 was somewhat above normal throughout the Park; the total precipitation for the year (September, 1942, to September, 1943) was above normal, and the mean temperature for the same period was below the average for the past ten years. The spring and the summer of 1943 began late, and exceptionally heavy snow fell even on June 1. Light snow fell on the higher peaks once or twice during each of the spring and summer months. As a consequence the glaciers bore more fresh snow at the end of the melting-season than ordinarily; yet the measurements made by Park Naturalist M. V. WALKER and his assistants show that all the glaciers had receded. It can only be concluded that the weather conditions, though on the whole more favorable for the maintenance of the ice-bodies than during past years, still fell short of the conditions that are required for their rehabilitation. The period of excessive wastage that threatened the glaciers in this part of the Rocky Mountains with early extinction, however, appears to have come to an end. Since the fall of 1941 recession of the ice-fronts has been relatively slight, indeed, insignificant as compared with the amounts recorded from 1936 to 1941.

Sperry Glacier from September, 1942, to September, 1943, had receded 21 feet, as compared with a mean of 75 feet during the past seven years and in contrast to a mean of 90 feet during the period of most rapid wastage.

Jackson Glacier had receded 15 feet, as compared with a mean of 71 feet during the past six years, and in contrast to a mean of 36 feet during the five years prior to 1942.

Grinnell Glacier had receded on an average about ten feet along its broad front, as compared with a mean of 46 feet during the past ten years, and in contrast to a mean of 71.5 feet during the period of most rapid wastage (1934 to 1941).

Measurements from a reference-point in front of the glacier to a boulder on the ice whose position had been determined in 1942, reveal that this boulder had moved forward about 50 feet

during the past 12 months. Though this may be due in part to sliding of the boulder, and possibly to its slipping from ice-pedestals, there can be little doubt that the shift in position is in the main representative of the forward movement of the ice in the glacier. As the boulder is now only about 50 feet from the ice-front, its rate of movement probably has been only a trifle faster than that of the ice at the extreme front. The latter, then, may have moved forward, say, 48 feet, and if so it must have receded by melting 48 feet plus ten feet (the amount of recession measured) -- that is, a total of 58 feet. This calculation, however rough, nevertheless is of value in that it strikingly shows up the fact, not generally appreciated, that the measured recession, from one year to the next, indicates really only a fraction of the total loss of ice which the glacier has suffered by melting at its terminus during the course of a year. The practice of making annual, or, for that matter, more frequent, measurements to readily identified boulders on the ice, a short distance back of a glacier's terminus, is strongly recommended to all observers who are in position to make repeated visits to specific glaciers.

Glaciers of Mount Rainier, Washington

As previous observers have had occasion to find out, correct determination of the amount by which each of the glaciers on Mount Rainier recedes or advances in the course of a year is by no means a simple matter, for the reason that most of those glaciers are so thickly mantled with rock-debris at their lower ends that the ice there is largely concealed from view. The termini of those glaciers are shapeless and indefinite, the moving ice passing by degrees into stagnant, so-called "dead" ice that is buried beneath chaotic piles of rock-waste. To decide at which point the "living" glacier ends and the permanent moraines begin, is in many instances impossible from the appearance of the surface-features alone. Clear ice, however, is usually exposed at and around the cavern-like portal from which the main stream of melt-water issues. The practice, therefore, has been to measure each year to the ice-walls flanking that portal. Those walls, however, are not straight in ground-plan; they usually deploy on both sides of the portal so as to form a roughly horseshoe-shaped recess in the glacier's terminus. The question therefore arises to which point, or points, in the recess the measurements should be taken. In glaciers with broad fronts lying on irregular ground, moreover, it happens sometimes that the melt-water changes its course beneath the ice, abandoning the portal to which measurements have been made for several years, and emerging at an entirely different point. It follows that the measurements recorded in past years have not been in every case truly representative of the shortening which each glacier has suffered as a whole.

Although these difficulties probably can never be eliminated altogether, a new plan of measuring has been introduced by HOWARD R. STAGNER, the new Park Naturalist of Mount Rainier National Park, that will doubtless yield a more truly representative record of the changes that are taking place in the configuration of the glaciers' termini. This plan consists in making each year a small outline map of the entire terminus with the aid of a light plane-table and a telescopic alidade. Being expert in the use of those instruments, STAGNER is able to map in a few hours the entire horseshoe-shaped recess and the adjoining parts of the terminus from one or two plane-table stations located accurately with reference to several permanent points established on ledges of rock in and at the sides of the vacated glacier-bed. By means of either stadia-measurements or intersecting lines of sight he determines the positions of a number of points at the base of the ice-wall, and others at the top of the wall. From vertical angles taken with the alidade he calculates the height of the ice-wall and thus determines the thickness of the glacier at its terminus -- a very important matter, concerning which the customary linear measurements furnish no information. Finally, from judiciously chosen plane-table stations he determines accurately the positions of prominent boulders on the glacier's surface. Comparison of such plane-table maps made in successive years will indicate very completely all the changes that are taking place, by the forward movement of the glaciers, by the melting of its ice-walls, by ablation at its surface, by spalling and caving off of the ice-front, by the lateral displacement of the stream-portal, and by the slumping of rock-debris. Each year's map is, of course, supplemented by suitable photographs.

During the fall of 1943 STAGNER made outline maps of the kind described of the terminal portions of the Nisqually, Paradise, Emmons, Carbon, and South Tahoma glaciers; photographic copies of those maps accompany his report. The method is so obviously superior to the customary plan of making one or more linear measurements by tape, that it is to be commended to all who annually visit glaciers in order to determine their recession or advance. For small glaciers it is perhaps unnecessarily elaborate, but for the larger ice-streams, more especially those in the Pacific Northwest, which suffer very considerable changes from year to year, it is particularly valuable.

The plane-table mapping, STAGNER stresses, requires but little more time than the making of linear measurements by tape. Most of the time required for recession-measurements on a glacier is, as a matter of fact, consumed in travel. A light plane-table and a small telescopic alidade together weigh less, and are less troublesome to transport over rough terrain, than a full-size engineer's transit.

In regard to the steep ice-walls that are associated with the stream-portals at the ends of the glaciers on Mount Rainier it should be explained that these ice-walls are as a rule concave in profile as well as in ground-plan. They are steepest at the top and intersect the surface of the glacier sharply, without any transitional curve. The glacier, in consequence, has the appearance of being cut off abruptly at the horseshoe-shaped recess, although the flanking portions of the terminus slope down more or less gradually. The true significance of these ice-walls is not yet wholly clear; it is hoped that STAGNER'S studies ultimately will shed light on the problem. Meanwhile it seems desirable to map each year the top, or crest-line, of the walls as well as the base. Indeed, the crest-line may in some instances afford a truer index of the recession than the base, for the base is often masked by fallen ice-blocks and rock-debris.

Nisqually Glacier on August 27, 1943, had receded 79 feet in exactly 12 months. However, the measurements which STAGNER made at intervals during that period reveal that in reality this recession was effected in only eight weeks, during July and August, 1943. On December 15, 1942, the terminus appeared to have advanced 46 feet since the preceding August 27; from December 15, 1942, until June 1, 1943, it remained practically unchanged in position; but by July 8 it had retreated nearly to the position which it occupied on August 27, 1942. The net recession reported for 1943 therefore took place entirely between July 8 and August 27, 1943.

In 1943 a recession of only two feet was reported for the Nisqually Glacier, but this, STAGNER has since discovered, was an error, due to a mistake in the identification of the point of reference for the measurements. The correct amount of recession for 1942 is 56 feet.

ARTHUR JOHNSON, of the Geological Survey, reports that the three profile-lines across the Nisqually Glacier, which had been established in previous years, were resurveyed once more in August, 1943. On the lower profile, which crosses the glacier about 3/4 mile above its terminus, at a mean altitude of 5,250 feet, the results were as follows: The eastern portion, 550 feet in length, showed but slight change since 1942, but the central portion, 350 feet long, had been lowered by ablation 20 feet on an average, and the western portion, 600 feet long, had been lowered 10 to 15 feet. The lowest point in the western portion, which has a concave, valley-like form, has gradually shifted westward during the past two years and has been lowered a total of 39 feet. As the glacier at this profile is probably not more than 200 feet thick, to judge from longitudinal profiles based on previous surveys, it seems likely that its lower portion, about one mile in length, will be destroyed entirely in about ten years, if reduction continues unabated at its present rate.

At the second profile-line, which crosses the glacier 1-1/4 miles above the terminus, and at a mean altitude of 6,000 feet, ablation appeared to have progressed somewhat more slowly. In the eastern portion of this profile, 300 feet in length, little change had taken place since 1942, but throughout the remainder of the profile, 1700 feet in length, the surface had been lowered 5 to 15 feet, the average being about eight feet.

At the third profile-line, which had been established in 1942 just below the confluence of the Wilson Glacier, about 1.9 miles above the terminus, and at a mean altitude of 6,750 feet, the Nisqually was found to have gained somewhat in thickness. In the eastern portion of the profile, 1000 feet in length, the gains were slight, but in the western portion, 600 feet in length, they ranged from five to ten feet. These gains are due probably to increased snowfall at the higher levels on Mount Rainier in recent years, but unfortunately there are no measurements of precipitation at those levels, and consequently there is no definite proof.

Paradise Glacier, unlike the other ice-streams here listed, lies spread out on a broad shelf, instead of confined within a canyon. As a consequence it has only slight eroding power and carries but little morainal debris. Its terminus, being fairly clean, slopes down gradually with convex curvature. At the end of August, 1943, the terminus was still partly covered with snow, and as a result no accurate measurement was possible. STAGNER estimates that in some places it may have advanced as much as 25 feet.

Emmons Glacier, in contrast to the Paradise, is heavily encumbered with debris in its terminal portion. Recession-measurements can be made only to the ice-walls exposed at the portal of the main melt-water stream - the source of White River - and these walls have melted back in recent

years so as to form a deep recess in the dirt-covered terminus. What is more, the glacier has been so greatly reduced in thickness by surface-ablation that the roof of the tunnel through which the stream flows beneath the ice is now beginning to collapse. The recess thus is likely to be suddenly increased in depth--or in length, depending upon the viewpoint--and the problem of obtaining a representative measurement of recession will be considerably aggravated. STAGNER'S measurements in 1943, made before the mouth of the tunnel had collapsed, show a recession of 150 feet since 1942.

Examination of the recession-record of previous years discloses several inconsistencies in the calculations. STAGNER therefore has recalculated the annual amounts and submits the figures of Table 1, which supersede those previously published.

Table 1

Year	Recession	Year	Recession	Year	Recession
1930[a]	. . .	1935	67	1940	97
1931	142	1936	193	1941	89
1932	2.5	1937	10	1942	72
1933	48.5	1938	107	1943	150
1934	15	1939	57	Total since 1930	1050

[a] Base-line established in 1930.

Carbon Glacier has always been one of the easiest to measure. It ends in a steep ice-wall that extends across the entire width of the terminus. As the crest-line is sharply defined and in all probability will remain so in the years to come, STAGNER proposes to make his measurements hereafter to the crest-line instead of to the more or less encumbered base of the ice-wall. His measurements in 1943 revealed a recession of 45 feet since 1942. The total recession since 1932 amounts to 380 feet.

South Tahoma Glacier, in contrast to the Carbon, is one of the most troublesome glaciers to measure, its terminal portion being cloaked by chaotic masses of morainal debris. The valley which it occupies, moreover, is broad, and as a consequence the melt-water stream often changes its course beneath the ice and abandons one portal for another. The recession-record of this glacier is therefore particularly unsatisfactory. The advance of 45 feet recorded in 1942, for example, does not represent an actual forward movement, but reflects merely a change in the position of the stream's portal. The same is true of the apparent advance of 17 feet recorded by STAGNER in 1943.

Glaciers of Mount Hood, Oregon

The report of KENNETH N. PHILLIPS, Chairman of the Research-Committee of the Mazamas, contains the significant statement that although the winter of 1942-43 brought perhaps the heaviest snowfall that has been recorded on Mount Hood in 20 years, and although the summer of 1943 was not marked by unusually high temperatures nor long periods of great warmth, nevertheless, by September 19, the glaciers had receded nearly, or quite, as much as in any of the last three years. On Mount Hood, therefore, as in Glacier National Park, excessive snow-precipitation did not stop the decline of the glaciers; in only one case it slowed up recession somewhat. It would thus appear that in the region about Mount Hood the climate has become sufficiently warmer in general to offset the effect of unusually heavy snowfalls. If those conditions persist unchanged, there is indeed little hope for the continued existence of the smaller glaciers on Mount Hood, and probably also of many glacierets on the other peaks of the Cascade Range in Oregon.

As was shown in the report of this Committee for 1941-42 [Trans. Amer. Geophys. Union, Part II, p. 382, 1943] probably all of the lesser glaciers on those peaks originated during the "little ice-age" of the last few thousand years, and are not remnants of the mighty ice-streams of the "great ice-age", or Pleistocene epoch. Only a few situated on the shady northerly slopes of the peaks may have persisted throughout post-Pleistocene time, in spite of the excessive warmth that then prevailed for several thousand years. It seems entirely possible, therefore, that the small glaciers of recent origin will succumb in the near future, if the climate continues to grow warmer, or even if its present warmth is merely maintained.

Eliot Glacier appeared to have receded 35 feet since September 20, 1942. A snow-drift at the terminus, however, prevented accurate measurement. In 1942 the recession amounted to 25 feet,

and in 1941 it amounted to 19 feet.

Coe Glacier had receded 19 feet, as compared with 41 feet in 1942.

Ladd Glacier had receded 12 feet, maintaining approximately the same rate of recession as in previous years.

To supplement these recession-measurements PHILLIPS and his associates determined the rate at which Eliot Glacier is being reduced in thickness by surface-ablation. To this end they resurveyed the two profile-lines which they had laid out across the lower part of the glacier in 1940. At the lower line, which is about 500 feet above the terminus, the surface was found to have been lowered about 12 feet in three years. Wastage is most rapid along the middle of the glacier, because there the mantling rock-debris is thinnest. At the upper line, where the ice is only scantily covered with rock-debris, ablation proceeds about 2-1/2 times as fast as at the lower line, the maximum rate, near the middle of the glacier, being about ten feet per year.

The implication of these facts in regard to the possible length of life of the glacier under present climatic conditions is of no little interest. If the ice at the upper profile-line be assumed to be 250 feet deep (a generous estimate, probably), then, at the present rate of wastage the entire lower half of the glacier is likely to be destroyed in 25 years. However, as the protecting mantle of rock-debris will gradually become thicker, the rate of surface-ablation will decrease; 25 years therefore is to be regarded as a minimum figure. It is possible, moreover, that at the lower end of the glacier, where rock-debris is most profuse, some masses of "dead ice" will remain preserved for an indefinite length of time beneath moraine-like hummocks of debris. For a fuller discussion of these possibilities the reader is referred to a paper on "Surface ablation and movement of the ice on Eliot Glacier", published jointly by FRANÇOIS E. MATTHES and KENNETH N. PHILLIPS [Mazama, pp. 17-33, 1942].

Glaciers of the Sierra Nevada, California

In 1943, as in previous years, Park Naturalist C. FRANK BROCKMAN states in his annual report, no attempt was made to measure the recession of any of the glaciers in and adjacent to Yosemite National Park, for the reason that the frontal margins of those glaciers are buried beneath strong terminal moraines of recent origin. The rate of surface-ablation, on the other hand, was again measured on each of the two lobes of Lyell Glacier, along profile-lines established in 1933.

For the first time since 1933 a substantial increase in thickness was recorded, due doubtless chiefly to the heavy snow-precipitation during the winter of 1942-43. So short are these glaciers that their lower ends reach hardly below the firn-line. Their surfaces lie almost entirely within the zone of snow-accumulation and are built up each winter, both by direct precipitation and by wind-drifting. In summer, on the other hand, they are exposed day after day, with few interruptions, to the radiant heat of the Sun, and most of the fresh snow is again melted away. The measurements made early in October, each year, therefore register the approximate balance between accretion and ablation. For virtually eight years this balance has been either negative or insignificant on the plus side. In 1943, however, the measurements show decided gains which, it is hoped, will mark a turn in the general trend of climatic conditions.

On the West Lobe of the Lyell Glacier the gains ranged from eight feet to a maximum of 12 feet; on the East Lobe they ranged from nine feet to 18 feet. Even so, these gains do not offset the total losses by ablation which these glaciers have suffered during past years. The surface of the West Lobe is now still five to nine feet lower than it was in 1933, and the East Lobe similarly shows a deficit of 13 to 19 feet since 1933.

No measurements were made on the Maclure, Dana, or Conness glaciers, but photographs were taken for comparison with photographs taken from the same stations in previous years. All of these glaciers, it is apparent, were substantially benefitted by the heavy snows and the unusually late advent of warm summer weather in 1943.

Glaciers of Alaska

The account published in the report of this Committee for 1942-43 [Trans. Amer. Geophys. Union, Part II, pp. 398-401, 1943], of the recorded variations of Portage Glacier and the other,

lesser glaciers that descend into Portage Pass, omitted mention of Lieutenant WHIDBEY'S findings in 1794, which it happens, throw particularly valuable light on the recent history of those glaciers. It seems desirable, therefore, to give here the following supplementary information, which is taken from "Alaskan glacier studies", by R. S. TARR and LAWRENCE MARTIN [Nation. Geog. Soc., 1914].

According to Captain Vancouver's report, Lieutenant WHIDBEY had been directed to explore Passage Canal and, on arriving at the head of that fiord, found himself at the entrance to a deep valley which transects the mountains at the neck of the Kenai Peninsula, and which has become known as Portage Pass. The description reads: "The isthmus itself was a valley of some breadth which, though it contained elevated land, was free from snow and appeared to be perfectly easy of access". WHIDBEY found no distinct path by which the Russians, and before them the Indians, were said to have carried on intercourse through this valley between Prince William Sound and Cook's Inlet, "but it did not appear to him that any particular track was necessary, as the valley has a tolerably even surface and was nearly destitute of any vegetable productions, and was equally passable in all directions. Its situation and character corresponded also with the description of it given by the Russians...."

Though it is possible that WHIDBEY might not have recognized a much depleted valley glacier when he saw one, it can hardly be doubted that he would have overlooked an ice-mass, 1,000 feet high, such as now blocks the pass. It may reasonably be concluded, therefore, that the Portage Glacier did not obstruct the pass at the time of WHIDBEY'S visit, and that travel through the pass then was unimpeded.

When, in 1880, IVAN PETROFF journeyed through this part of Alaska while taking the census [Tenth Census of the United States, 1880, vol. 8, 1894] he found that "a glacial formation forms the portage route between Chugatch Bay (now called Prince William Sound) and Cook's Inlet", and this so-called glacial formation he showed on his map as a glacier corresponding closely to the Portage Glacier in its present general form. The map by S. APPLEGATE in GEORGE DAVIDSON'S report on "The glaciers of Alaska that are shown on Russian charts or mentioned in older narratives", [Trans. and Proc. Geog. Soc. Pacific, 2nd ser.,vol. 3, pp. 1-98, 1904] likewise shows Portage Pass occupied by a glacier. It is thus evident that the pass was invaded by the Portage Glacier at some time between 1794 and 1880. This confirms the inference in this Committee's report for 1942-43 that the Portage Glacier and the other glaciers in the vicinity of Portage Pass made their main advance "at some time during the nineteenth century, possibly as late as during the second half".

WHIDBEY'S description of Portage Pass, it should here be pointed out, contains two items that may throw some light on the earlier history of the glaciers. The "elevated land" within the Pass suggests the presence of moraines, or possibly even of low debris-covered masses of "dead ice", vestiges of a previous ice-advance. And the absence of "vegetable productions", though probably not to be taken literally, doubtless indicates absence of forest trees. As spruce and fir grow well near sea-level in this part of Alaska, their absence very probably implies that Portage Pass had been evacuated by the melting of the glaciers only a short time prior to WHIDBEY'S visit in 1794.

U. S. Geological Survey,
Washington 25, D. C.

REPORT OF THE COMMITTEE ON TRANSPIRATION AND EVAPORATION, 1943-44

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In the following statements the members of this Committee have outlined at least a partial summary of current progress in research on transpiration and evaporation.

E. A. COLMAN--Last year's Committee report described an analysis, then under way, of the annual soil-water cycles in the four types of lysimeters which form the San Dimas installation. This study was carried on in order to determine the extent to which vegetation water-economy data obtained in one kind of lysimeter would agree with that obtained in other kinds. The analysis has

been completed and a manuscript prepared for publication under the title of "A study of the relative performance of four types of lysimeters". It was shown that when compared on the same dates a linear relationship existed between the water-content of confined lysimeters 24 inches and 38 inches deep, but between them and the confined lysimeters 72 inches deep, no definite relationship was found. Comparisons between the confined lysimeters and a six-foot deep block of the same soil provided with free-draining soil-to-soil seepage-contact, showed no unique or predictable relationship between them. In short, the soil-water cycle in one type of lysimeter is not related with any degree of assurance to the cycle in any other kind. These findings indicate that serious difficulties may be encountered in any lysimeter-study of vegetation water-economy if an attempt is made to compare results from lysimeters of different depth or type since the findings might be influenced by the characteristics of the lysimeters themselves.

The successful use of lysimeters depends upon the possibility of successfully duplicating all environmental conditions of natural soil-blocks within the confining walls of the lysimeters. This requirement has been recognized by many workers and has been emphasized in earlier reports of this Committee. But the accomplishment of this duplication has not yet been demonstrated.

In the San Dimas installation the unnatural lysimeter-environment is due, in great part, to the influence upon seepage of the interface between soil and air at the base of the soil-columns. Elimination of the saturated soil-layer resulting from the interface may require important changes in the design of lysimeter seepage-facilities.

The lysimeter drainage-modification being studied on the San Dimas Experimental Forest involves the introduction into the base of the lysimeter-soil of porous fired-clay cups within which water-tensions of any desired magnitude can be maintained. This method was suggested by E. F. WALLIHAN [J. Amer. Soc. Agron., vol. 32, pp. 395-404, 1940] and appears to be theoretically sound. By the present method of draining confined lysimeters, seepage cannot continue after the water-pressure at the base of the soil-column has dropped below zero (atmospheric pressure) so that the lowest soil-layer is bound to be well above its normal field-capacity when seepage has stopped. If the proper tension is applied to the soil-water at the seepage-plane, it should be possible to drain the soil there to its field-capacity and thus make the lysimeter-soil more nearly comparable to a like depth of naturally drained soil.

In a recent study using soil columns seven inches in diameter and six feet long we have found that a tension of 150 cm of water maintained at its base was sufficient to reduce moistures throughout the column below the field-capacity. Fifty cm of water-tension, however, appears not to be sufficient to drain the soil to its field-capacity, indicating that the proper tension lies between these two.

If analysis of the "model" study shows that drainage under tension results in satisfactory soil-moisture conditions the method will be tried on a larger scale in the 38-inch deep lysimeters that support stands of grass. Comparisons will be made of the soil-water cycles and grass-yields between lysimeters so treated and those provided with the present soil and air-seepage interface. It is anticipated that such a study will demonstrate the possibility of applying the tension-method of lysimeter moisture-control to the large confined lysimeters of the San Dimas installation.

N. W. CUMMINGS (letter of June 23, 1943)--I can report having almost completed a paper in which it has been possible to derive the BOWEN equation by using the well-known equations of continuity and heat-conduction, together with the fundamental, as distinguished from the somewhat speculative, equations in the modern theory of turbulence. This derivation removes all need for doubtful approximations which have appeared in some recent literature. It also removes any possible vagueness as to the physical reality of the BOWEN relation, and clears up a misunderstanding which seems to have arisen regarding the manner in which the observations need to be made for the proper application of the equation.

The paper also attempts to clear up certain misconceptions which in the past have been common among persons interested in evaporation.

A. R. CROFT--A short pilot experiment was conducted on the Wasatch Plateau, at elevation 8,700 feet, in 1942, to try a proposed method for determining snow-evaporation. The method consists of filling evaporation-cans, six inches deep and six inches in diameter, with cores of surface-snow and ascertaining evaporation by loss of weight. Records of wind-velocity and vapor-pressure gradients of air were made. A summary of results follows:

Evaporation as influenced by site-factors is shown by the following losses, in inches of water, on May 8: (1) In shade with free wind-movement, 0.052 inch; (2) in Sun with free wind-movement, 0.054 inch; (3) in Sun with no wind-movement, 0.023 inch. The influence of vapor-pressure gradient of the air is indicated by the following results: With relatively high gradients on May 8, 9, and 10, evaporation in inch of water was 0.070, 0.060, and 0.059, respectively; and for relatively low gradients on May 19, 20, 21, evaporation, in inch, was 0.006, 0.008, and 0.005, respectively.

Using average daily evaporation-rates the following monthly totals were calculated: For a period of relatively high vapor-pressure gradient, April 28 to May 8, 1.60 inches; for a period of relatively low vapor-pressure gradient, May 9 to 12, 0.027 inch; for the average of all gradients between April 28 and May 21, 1.0 inch.

Evaporation from sunset to sunrise was only slightly less than from sunrise to sunset. None of the daily results indicated that condensation of moisture from the atmosphere ever exceeded evaporation. However, conditions favorable for condensation existed for short periods of several days.

M. D. HOOVER--The work of the Division of Forest Influences has been reduced to a maintenance basis. To date, it has been possible to continue routine precipitation and stream-flow records which will allow the interpretation of the watershed-treatments already made and permit continuation of the Station's program at the close of the war.

On the Coweeta Experimental Forest, three watersheds have received treatments which will yield information concerning the transpiration of a dense hardwood forest-cover in the super-humid region of the Southern Appalachians. On a 40-acre watershed all woody vegetation was cut in the winter of 1939-40. Great care was taken to prevent disturbance to the surface-soil, no logs were removed from the area and all slash and brush were cut to lie close to the ground and evenly scattered. Natural regrowth has been allowed. A 33-acre drainage-area was cut-over in a similar manner in 1940-41 but new growth was cut in the growing seasons of 1941 and 1942. A more complete description and preliminary results will be presented before the Section of Hydrology. In the first year after treatment, runoff was increased by almost 17 inches on both watersheds. In the second year, runoff was increased 9-1/2 inches on the watershed where natural growth was allowed and 13 inches where the sprouts were cut. The increase in runoff is a result of the higher soil-moisture on the treated watersheds which causes a larger proportion of rainfall to be added to ground-water storage.

The third treatment was planned to determine the influence of vegetation growing along the stream-channel where roots have continuous access to the water-table. On a 23-acre watershed all vegetation which was less than 15 feet above the stream-course was cut. The area cut-over was 2.6 acres. This treatment was carried out in one week during July when demands of transpiration were large. Previously stream-flow had shown considerable diurnal fluctuation but none was shown after treatment.

J. KITTREDGE--While my own work during the past year has not progressed, as far as the evaporation-transpiration phases are concerned, I should like to call attention to a study made by THEODORE T. KOZLOWSKI of transpiration losses by three-year-old forest trees during the dormant season, [Transpiration rates of some forest tree species during the dormant season, Plant Physiology vol. 18, pp. 252-260, 1943]. On a unit-area basis, the author found no great difference between the foliar transpiration of two conifer species and the stem-transpiration of three (leafless) hardwood species. An evergreen hardwood (cherry laurel), on the other hand, exhibited relatively high transpiration-rates.

Transpiration by loblolly and eastern white pine was found to decrease with declining soil-temperature, over a range from 17° to 0° C.

P. B. ROWE--Investigations to determine the influence of forest-vegetation and land-use on evaporation-transpiration losses were started by the California Forest and Range Experiment Station as early as 1928. These early studies, however, were largely of the runoff-plot and lysimeter type and yielded results principally of qualitative value. A series of studies of interception and stemflow, snow-evaporation, and soil-moisture was started in 1934 to supplement the results of the plot- and lysimeter-studies and to obtain quantitative data on evaporation- and transpiration-losses, particularly as these affected the soil and sub-surface water-storage and runoff-relations. These studies were started in the woodland-chaparral type of the Sierra Nevada foothills at North Fork, California, and have since been extended to second-growth ponderosa pine and woodland-grass types in the Sierra Nevada foothills and to chaparral types of the San Dimas Experimental Forest in southern California.

The studies have shown that, under California conditions of heavy rainfall in winter and very light rainfall in summer, interception-losses due to direct evaporation from the vegetation are much lower than previously supposed. In moderately dense stands of chaparral, annual evaporation-losses from interception have averaged only four to eight per cent (1.5 to 2.0 inches) of the total precipitation. In a 60- to 80-year-old fully stocked stand of ponderosa pine the losses were somewhat greater but averaged less than 15 per cent (7.5 to 9.0 inches) of the total annual precipitation.

Interception of precipitation by the vegetation also greatly influenced the distribution of rainfall reaching the ground and consequently its effect on infiltration and soil-moisture relations. In both chaparral and forest types, the storm-catch of individual rain-gages placed beneath the canopy varied from a very small proportion to more than twice the average catch of all gages in the type being sampled. Although in ponderosa-pine stands the amount of annual precipitation reaching the soil as flow down the stems was only two to five per cent of the total precipitation, in chaparral stands it averaged from 15 to 20 per cent of the total precipitation.

Soil-moisture-sampling studies, although time-consuming, have yielded much valuable and needed information on the influence of natural vegetation on the rate and amount of soil-evaporation-transpiration losses. The outstanding finding of these studies was that evaporation-transpiration losses of moisture stored in the soil at the end of the rainy season were not appreciably reduced by annual burning or other manipulation of the natural vegetation. During winter and early spring, when the soils contained water readily available for plant-growth, however, the evaporation-transpiration rates of the undisturbed and more densely covered plots were slightly greater than those from similar plots in which the density of the natural vegetation-cover had been reduced by burning, grazing, or other causes. This, in general, resulted in slightly greater annual evaporation-transpiration losses from the more densely covered plots. On the other hand, reduction in the vegetation sufficient to affect appreciably the evaporation-transpiration losses resulted without exception in lower infiltration-capacities of the soil. Thus, any gains in soil-moisture from reduced evaporation-transpiration were usually far outbalanced by reductions in infiltration.

An interesting and important application of the interception and evaporation-transpiration data has been their use in the hydrologic analyses of several United States Department of Agriculture flood-control surveys conducted in California. Modified to fit local conditions by soil-moisture sampling and by analyses of the rainfall-runoff relations of small drainage-areas, these data facilitated more accurate evaluation of the factors affecting the storm and seasonal disposition of precipitation. They were especially valuable in computing such items as available soil and sub-surface water-storage capacities, and surface and sub-surface runoff-rates and amounts. The flood-control-survey analyses, as well as the plot-studies, showed that, although the combined interception and soil evaporation-transpiration losses were normally slightly higher in areas with good protective vegetation-cover than in similar areas with poor or freshly burned vegetation cover, such losses were usually more than compensated by reduced flood-flows and a more equable distribution of stream-flow.

C. W. THORNTHWAITE--Last year I spent several months in Mexico on special assignment to the Mexican Government. One of my tasks was to work with the technical men in the Irrigation Commission, in making a map of the Republic showing supplementary needs for water for irrigation. Few data were available to me in Mexico City and since my return to Washington I have continued the investigation.

I obtained all of the data I could find on monthly water-losses from land-areas in different parts of the country. These include consumptive-use data from various irrigation-districts in the West and the data on evapotranspiration from different types of cover on our weighing lysimeters at Coshocton, Ohio. I also computed water-loss from some small watersheds from values of precipitation and runoff for months when it was apparent that there was no reduction of evapotranspiration because of a moisture-deficiency in the soil and where it was possible to estimate the lag in runoff and thus to assign the runoff to the month when the rainfall occurred.

From these observations it was evident that there is no simple relationship between monthly evapotranspiration and monthly temperature such as LOWRY and JOHNSON, and WILLIAMS [see 1 and 2 of "References" at end of paper] attempt to demonstrate for annual values. For a single place the values of evapotranspiration for a standard month of 30 days, each having 12 hours of possible sunshine, are well expressed by an equation of the form

$$e = ct^a \qquad (1)$$

in which e is monthly evapotranspiration in cm and t is mean monthly temperature in °C. But an equation derived for a station in a warm climate does not yield correct values for one in a cold climate, and vice versa. For a given monthly mean temperature the evapotranspiration rate is greater in cool climates than in warm. Evapotranspiration is, of course, restricted when precipitation is deficient but it appears to be quite independent of precipitation at other times. However, since some months with deficient precipitation occur nearly everywhere, two aspects of evapotranspiration, potential and actual, must be recognized. Potential evapotranspiration is the water-loss which will occur if at no time there is a deficiency of water in the soil for the use of vegetation. The term "consumptive use", familiar in irrigation-literature, is equivalent to potential evapotranspiration. Actual evapotranspiration may be the same as potential evapotranspiration in rainy climates but it is more often smaller because of deficient rainfall at some time of the year. LOWRY and JOHNSON did not recognize this distinction nor do other irrigation-engineers in their published writings [3].

As a heat-factor for inclusion in the general formula I have used a modified form of the temperature-efficiency (T - E) - index that is an integral element of my classification of climate [4]. It is well suited to this purpose because it ranges in value from zero at the outer margin of the climate of perpetual frost by multiples of 16 to 128 at the poleward margin of tropical climates. There is a relation between (T - E) and the exponent "a" that is very closely approximated in the (T - E)-range between ten and 150 by the expression

$$a = 0.000000675\,(T-E)^3 - 0.0000771\,(T-E)^2 + 0.01792\,(T-E) + 0.49239 \qquad (2)$$

The general equation for unadjusted potential evapotranspiration is then

$$e = 1.6\,[10t/(T-E)]^a \qquad (3)$$

in which "a" has the value given in (2) above.

The formula gives unadjusted rates of potential evapotranspiration. Since the number of days in a month varies from 28 to 31 (nearly 11 per cent) and the number of hours in the day between the onset of evapotranspiration in the morning and its termination in the evening varies with the season and with latitude it becomes necessary to reduce or increase the unadjusted rates by a factor that varies with the month and the latitude. These factors are given in a table.

Of course, the data already used for deriving the formula cannot be used for checking its validity. Still a comparison of computed and observed values will show how accurately the formula describes the data that went into it. The comparison is very good. I have had access to some other consumptive-use data, chiefly those published by LOWRY and JOHNSON [5] and BLANEY [6] that could not be used in the development of the formula because they were annual totals only. They serve as checks, however, because I can get a comparable computed annual figure by summation of the monthly values. The data of consumptive use in irrigated valleys, published by LOWRY and JOHNSON, together with my computations from Weather Bureau temperature-data of potential evapotranspiration are given in Table 1. Monthly values of potential evapotranspiration for these stations are given in Table 2. It is interesting that consumptive use of Barahona in the Dominican Republic that falls far from the line in the figure of LOWRY and JOHNSON is very closely approximated in my computation. Comparisons between BLANEY'S consumptive use data of the Upper Rio Grande Valley and my computations of potential evapotranspiration from temperature-data of various Weather Bureau stations are equally close.

The consumptive-use data that have been available to me do not provide a sufficient check, so I have turned to the runoff data of the United States Geological Survey and others for additional material. The National Resources Board in the report of December, 1934, published a map of average annual runoff. KITTREDGE [7] used this map in connection with one of rainfall to make a map of annual water-loss, or actual evapotranspiration.

By comparing computed monthly values of potential evapotranspiration with monthly precipitation I obtain values of actual evapotranspiration. When these are subtracted from the precipitation the result is water available for runoff. In order to obtain the monthly runoff a storage-factor, appropriate to the size of the watershed must be introduced. The actual evapotranspiration can be determined in this manner only by taking account of a suitable amount of non-gravitational water in the soil available to the plants. Wherever I have tried the method so far (mostly east of the 100th meridian) ten cm or four inches works and a larger or smaller figure fails. This represents the amount of water in the root-zone that is available to the plants and that may appear as evapo-

Table 1--Comparative data on irrigated valleys in western United States

No.	Valley	State	Weather Station	Observed consumptive use	Computed potential evapo-trans.	Difference	Difference
				cm	cm	cm	pct
1	New Fork	Wyoming	Pinedale, Wyo.	46.6	45.4	-1.2	2.6
2	Michigan and Illinois	Colorado	Walden, Colo.	45.7	46.9	1.2	2.6
3	S W Area, San Luis	Colorado	San Luis, Colo.	53.0	51.8	1.3	2.4
4	West Tule Lake	California	Tule Lake, Calif.	67.7	57.9	-9.8	14.5
5	Garland Div. Shoshone	Wyoming	Lowell, Wyo.	61.6	59.3	-2.3	3.7
6	North Platte	Wyo.-Nebr.	Torrington, Wyo.	60.4	60.7	0.3	0.5
7	Mason Creek and Boise	Idaho	Caldwell, Idaho	66.1	66.5	0.4	0.6
8	Uncompahgre	Colorado	Delta, Colo.	68.3	67.5	-0.8	1.2
9	Mesilla	N.Mex.-Tex.	Agr.College, N.M.	83.2	84.0	0.8	0.9
9a	Greenfields Div. Sun River	Montana	Great Falls, Mont.	60.3	60.2	-0.1	0.2
9b	Pecos River near Carlsbad	N.Mex.	Carlsbad, N. Mex.	89.6	91.7	2.1	2.3
	Lower Rio Grande	Tex.	Del Rio, Tex.	115.8	117.0	1.2	1.0
	Barahona	Dom. Republic	Barahona	147.3	146.3	-1.0	0.7

Table 2--Monthly distribution of potential evapotranspiration for various Weather Bureau Stations, in centimeters
(Computed by T-E method)

Stations	Month												Year
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	
Pinedale, Wyo.	0.0	0.0	0.0	1.3	5.7	9.0	11.4	9.6	5.9	2.5	0.0	0.0	45.4
Walden, Colo.	0.0	0.0	0.0	1.8	6.3	9.0	10.8	9.9	6.4	2.7	0.0	0.0	46.9
San Luis, Colo.	0.0	0.0	0.7	3.3	6.5	9.4	11.1	9.9	7.0	3.6	0.3	0.0	51.8
Tule Lake, Calif.	0.0	0.0	2.1	4.3	7.1	9.5	11.8	10.5	7.0	4.3	1.1	0.2	57.9
Lowell, Wyo.	0.0	0.0	0.1	4.0	7.8	11.4	14.0	11.9	7.0	3.1	0.0	0.0	59.3
Torrington, Wyo.	0.0	0.0	0.8	3.8	7.4	11.1	13.8	12.1	7.5	3.5	0.7	0.0	60.7
Caldwell, Idaho	0.0	0.4	2.3	4.9	8.0	11.2	14.6	12.4	7.6	4.0	1.1	0.0	66.5
Delta, Colo.	0.0	0.0	2.0	4.8	8.4	11.9	14.6	12.5	8.2	4.1	1.0	0.0	67.5
Agri.College, N.M.	0.9	1.5	3.3	5.6	9.4	14.2	16.0	14.3	9.7	5.9	2.4	0.8	84.0
Great Falls, Mont.	0.0	0.0	0.3	4.2	7.7	10.9	13.7	11.9	7.0	3.8	0.7	0.0	60.2
Carlsbad, N. Mex.	1.0	1.5	3.8	6.6	11.2	15.5	16.8	15.4	10.8	5.9	2.4	0.8	91.7
Del Rio, Tex.	1.5	2.3	5.2	8.6	13.7	19.4	20.2	19.7	14.0	7.7	3.3	1.4	117.0
Barahona, Dominican Repub.	8.6	8.2	10.0	11.2	13.9	15.0	16.2	15.8	14.3	13.1	10.8	9.2	146.3

transpiration. I should expect this figure to vary with soil-type; it probably does within certain limits. Of course it does not include gravitational water which appears later as runoff. Sample computations for Columbus, Ohio, and Clarinda, Iowa, follow in Table 3. The values are in cm.

I have under preparation maps of temperature-efficiency (T - E), potential evapotranspiration, actual evapotranspiration, precipitation-deficiency, and runoff for the eastern part of the United States. The maps of actual evapotranspiration and runoff are presented as Figures 1 and 2. The runoff-map made by plotting the computed values checks very well with the original runoff-map prepared by the National Resources Board. It has revealed some admitted errors on the original.

Table 3--Evapotranspiration, runoff, and moisture-deficiency in Columbus, Ohio, and Clarinda, Iowa, in centimeters

Item	Month												Year
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	
Columbus, Ohio													
T°, C	- 1.61	- 0.83	4.39	10.61	16.61	21.44	23.89	22.61	19.28	12.72	5.61	0.22	11.22
(T-E)	0.0	0.0	.82	3.12	6.15	9.04	10.68	9.82	7.73	4.10	1.19	.01	52.66
Potential evap.	0.0	0.0	1.3	4.4	9.1	12.8	14.9	13.0	9.3	4.9	1.5	.2	71.4
Precipitation	7.8	6.9	8.7	7.3	9.0	8.5	9.0	8.2	6.4	6.2	7.0	6.9	91.9
Storage-change	0.0	0.0	0.0	0.0	- .1	-4.3	-5.6	0.0	0.0	1.3	5.5	3.2	
Storage	10.0	10.0	10.0	10.0	9.9	5.6	0.0	0.0	0.0	1.3	6.8	10.0	
Actual evaporation	0.0	0.0	1.3	4.4	9.1	12.8	14.6	8.2	6.4	4.9	1.5	.2	63.4
Precip. deficiency	0.0	0.0	0.0	0.0	0.0	0.0	0.3	4.8	2.9	0.0	0.0	0.0	8.0
Available for RO	7.8	6.9	7.4	2.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.5	28.5
Runoff	4.8	5.8	6.6	4.8	2.4	1.2	.6	.3	.1	.1	0.0	1.8	28.5
Clarinda, Iowa													
T°, C	- 5.33	- 3.61	3.89	10.56	16.28	21.61	24.33	23.44	18.94	12.11	3.89	-3.17	10.22
(T-E)	0.0	0.0	0.69	3.12	5.98	9.17	10.95	10.35	7.49	3.81	0.69	0.0	52.25
Potential evap.	0.0	0.0	1.1	4.4	8.9	13.0	15.4	13.7	9.0	4.6	0.9	0.0	71.0
Precipitation	2.3	2.8	4.1	7.1	11.3	12.7	10.5	8.8	9.7	6.8	3.6	2.6	82.3
Storage-change	1.8	0.0	0.0	0.0	0.0	- 0.3	- 4.9	- 4.8	0.7	2.2	3.7	2.6	. . .
Storage	10.0	10.0	10.0	10.0	10.0	9.7	4.8	0.0	0.7	2.9	5.6	8.2	. . .
Actual evaporation	0.0	0.0	1.1	4.4	8.9	13.0	15.4	13.6	9.0	4.6	0.9	0.0	70.9
Precip. deficiency	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.1
Available for RO	0.5	2.8	3.0	2.7	2.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	11.4
Runoff	0.3	1.5	2.3	2.5	2.4	1.2	0.6	0.3	0.2	0.1	0.0	0.0	11.4

For example, there is a discrepancy between the two maps in western Virginia, western North Carolina, and eastern Tennessee. On the National Resources Board map runoff is shown as grading from 20 inches to 25 inches and above. On my map there is a zone in eastern Tennessee and western Virginia in which the runoff is under 20 inches and within this zone a narrow strip in which it is under 15 inches.

Only a couple of weeks ago a new runoff-map of this area became available to me. It is published in the annual summary of precipitation in the Tennessee River Basin for 1943, and is based on annual totals of runoff for 124 minor watersheds in the valley. The close correspondence between these data and my computations everywhere in the valley is astonishing, especially since the data of the Tennessee Valley Authority are for a uniform period from 1920 to 1942 and my computations are from averages of temperature and precipitation for various periods prior to 1930. Furthermore, the data of the Tennessee Valley Authority refer to areas ranging in size from a few square miles to nearly two thousand whereas my computations refer to points where the weather observations were made (see Fig. 3).

I have checked the formula further by making comparisons of computed runoff with the actual observations for individual watersheds for long series of years. This procedure involves the problem of getting true values of monthly precipitation for watersheds of considerable area. For one test I selected the James River Basin in Virginia. The Weather Bureau publishes separate averages of temperature and precipitation for the Great Valley of Virginia. The two areas differ considerably but to avoid the labor of determining average monthly values of temperature and precipitation for the James River Basin I made the computations for the Great Valley. On the whole there is close agreement between the two sets of figures. Usually when runoff differs precipitation differs in the same direction, which suggests that my computation of actual evapotranspiration is not much in error (see Table 4). I made similar computations for a number of other watersheds with acceptable results. I have not been primarily interested in developing a runoff-equation, but rather in using runoff-measurements to check my computations of evapotranspiration. Therefore I have not given much study to the matter of seepage-storage; I anticipate that such an investigation would result in an improvement in the correspondence between the monthly computations of runoff and the actual observed values.

There are still many unanswered questions in my mind, but space here does not permit me to state them. An implied conclusion of this study is that evapotranspiration is independent of the character of the plant-cover, of soil-type, and of land-utilization to the extent that it varies under

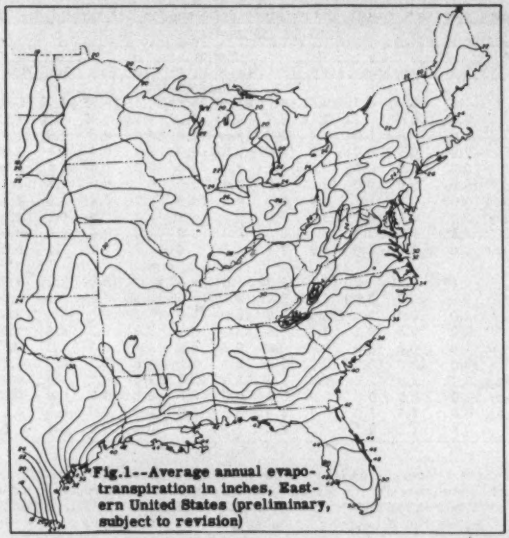

Fig.1--Average annual evapotranspiration in inches, Eastern United States (preliminary, subject to revision)

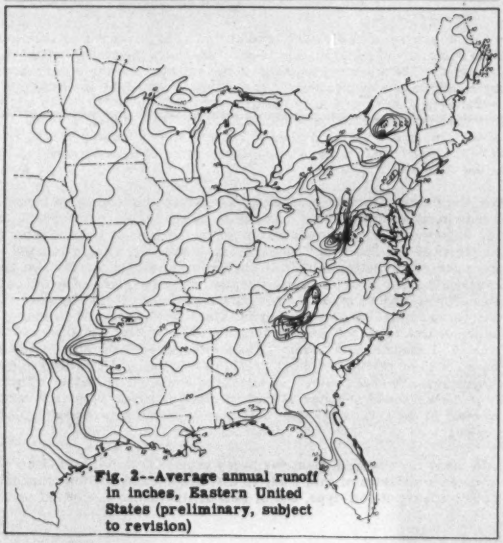

Fig. 2--Average annual runoff in inches, Eastern United States (preliminary, subject to revision)

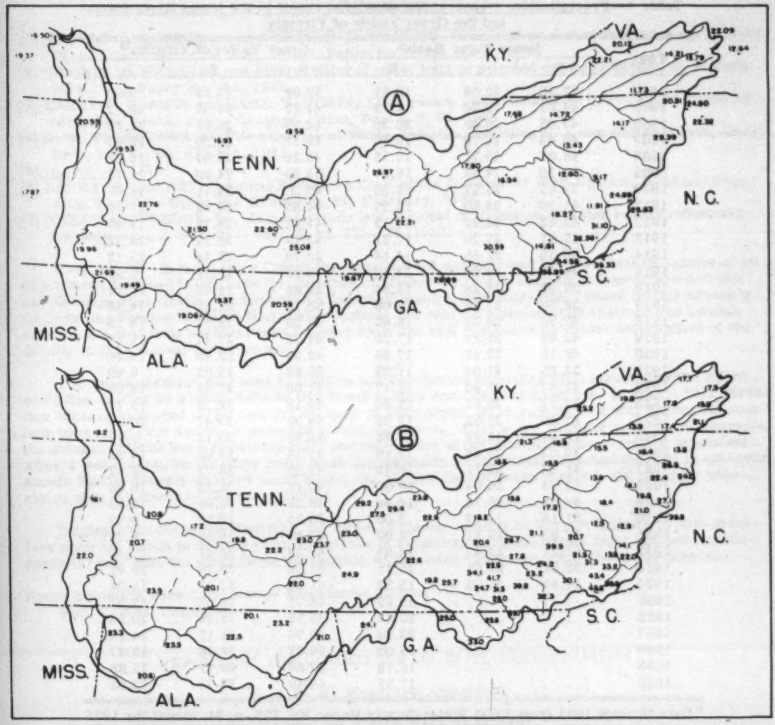

Fig. 3--Mean annual runoff in Tennessee River Basin: (A) runoff computed by (T-E)-method from data for temperature and precipitation at Weather Bureau stations (in inches), period of record variable ending in 1930; figures refer to points of weather observations; (B) observed runoff (in inches) adjusted to uniform period, October, 1920, through September, 1942 (From Tennessee Valley Authority, Hydraulic Data Division, Precipitation in Tennessee River Basin Annual 1943); figures refer to watersheds varying in area from 10 to 2200 square miles

ordinary conditions. This conclusion is contrary to currently accepted notions concerning evapotranspiration-losses and I am reluctant to accept it myself; however I have not yet found a reason for denying it. Of course, it is clear that the evapotranspiration regime can be altered. Destruction of vegetation will eliminate transpiration and mulching of bare soil will greatly reduce evaporation. But such practices are not carried out on a wide scale and surely could not modify the evapotranspiration map of the United States.

I have always supposed that the natural vegetation of western Iowa was prairie because the climate is subhumid and that of central Ohio was mixed mesophytic forest because the climate is humid. However, the actual situation is different, as the data for Columbus and Clarinda show.

Table 4--Precipitation, evapotranspiration, and runoff in the James River Basin and the Great Valley of Virginia

Year	James River Basin[a]			Great Valley of Virginia[b]		
	P	E	R	P	E	R
1904	32.30	22.09	10.21	32.99	23.15	9.80
1905	44.01	29.26	14.75	41.93	26.85	13.43
1906	47.05	26.85	20.20	48.55	26.81	21.10
1907	44.44	24.79	19.65	45.11	24.09	20.87
1908	45.08	25.72	19.36	45.28	25.95	19.84
1909	34.20	17.83	16.37	38.89	24.80	16.14
1910	39.43	26.57	12.86	40.00	24.41	14.65
1911	41.39	28.60	12.79	44.85	26.22	17.76
1912	42.42	24.69	17.73	41.81	24.76	17.95
1913	45.01	27.70	17.31	43.19	26.93	16.22
1914	36.59	22.45	14.14	38.78	22.24	15.12
1915	41.19	24.09	17.10	41.69	25.91	15.95
1916	37.92	25.28	12.64	39.84	15.87	15.12
1917	36.56	23.50	13.06	36.10	22.21	14.88
1918	45.30	28.35	16.95	47.28	26.77	18.19
1919	42.49	25.23	17.26	41.73	27.44	15.39
1920	45.15	27.89	17.26	40.99	23.98	16.34
1921	32.89	21.04	11.85	35.63	28.03	8.90
1922	41.67	25.90	15.77	41.06	27.36	13.66
1923	37.71	25.63	12.08	40.12	26.14	13.27
1924	47.30	27.52	19.78	44.30	23.47	20.28
1925	28.84	18.98	9.86	28.90	20.12	9.65
1926	39.67	26.48	13.19	41.14	23.86	14.92
1927	41.84	26.11	15.73	42.05	26.77	16.42
1928	42.94	26.04	16.90	40.16	25.12	16.30
1929	44.56	25.76	18.80	46.02	25.95	19.13
1930	21.16	14.16	7.00	23.70	18.58	6.73
1931	37.31	29.31	8.00	37.25	28.50	9.72
1932	44.21	29.37	14.84	45.23	24.41	17.40
1933	38.01	22.86	15.15	37.99	25.79	15.91
1934	44.43	31.10	13.33	41.34	27.28	11.34
1935	....	....	19.99	46.73	29.06	17.87
1936	....	....	20.44	45.59	25.00	20.28
1937	....	....	23.08	49.76	25.12	24.53
1938	....	....	13.08	39.37	26.58	13.27
193	....	....	12.78	37.68	26.81	12.68
1940	....	....	17.31	44.49	23.94	18.66

[a] Data through 1934 from USGS Water-Supply Paper No. 772, p. 84; runoff for 1935 through 1940 from other Water-Supply Papers; evapotranspiration equals precipitation minus runoff.

[b] Evapotranspiration and runoff computed by (T-E) method from temperature and precipitation data in USWB Climatological Data for the United States, by Sections. Evapotranspiration plus runoff does not equal rainfall because of changes in soil-moisture and seepage-storage.

Item	Columbus	Clarinda
Potential evapotranspiration (inches)	28.11	27.95
Precipitation (inches)	36.18	32.40
Actual evapotranspiration (inches)	24.96	27.91
Runoff (inches)	11.22	4.49
Precipitation deficiency (inches)	3.15	0.04

The potential evapotranspiration is the same in both places and although there is nearly four inches less precipitation at Clarinda than at Columbus, its distribution through the year is so much more nearly parallel to that of potential evapotranspiration that more of it is available to the plants. The actual evapotranspiration is three inches greater in Clarinda than in Columbus and the runoff is nearly seven inches less. Thus, one must conclude that the climate of western Iowa is more humid than that of central Ohio.

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H. G. WILM--In last year's Committee report were summarized the preliminary results of an experiment designed to evaluate the influence of timber-cutting on autumn soil-moisture deficits and on evapotranspiration losses under a forest of mature lodgepole-pine. Based on one season's records, the results indicated that timber-cutting had exerted a pronounced effect on the autumn deficits, but that total seasonal water-losses from the soil seemed to be rather independent of the density of the residual forest-cover.

Two more seasons' data tend to confirm our conclusion regarding total losses, but the effect of timber-cutting on autumn deficits was found to vary considerably from year to year. This variation seemed to depend largely on the amounts of net rainfall which reached the soil during the summer preceding each autumn's sampling of soil-moisture. After a dry summer season, for example, the autumn deficits were relatively high, and were much alike under all timber-cutting treatments. After a wet season, on the other hand, when substantially more rainfall reached the soil in cut-over stands than in densely-covered uncut areas, the autumn deficits were directly and strongly associated with the intensity of timber cutting.

Judging from these observations, the effect of timber-cutting on autumn deficits in soil-moisture does not result primarily from variations in evapotranspiration losses from the soil, but depends largely upon the amounts of net rainfall which reach the soil to replenish these losses.

Rocky Mountain Forest and Range Experiment Station,
Fort Collins, Colorado.

REPORT OF THE COMMITTEE ON INFILTRATION, 1943-44

G. W. Musgrave, Chairman

The Committee comprises several Sub-Committees as follows:

(1) Infiltration and the Physics of Soil-Moisture and of the Infiltration-Process
B. T. Shaw (Chairman) F. L. Duley Willard Gardner
S. J. Richards
(2) Infiltration in Relation to Ground-Water
Walter N. White (Chairman) S. W. Lohman Samuel F. Turner
(3) Infiltration in Relation to Snow and Its Physical Properties
Walter T. Wilson (Chairman) G. D. Clyde B. T. Shaw
(4) Infiltration in Relation to Irrigation
M. R. Lewis, (Chairman) Harry F. Blaney Howard L. Cook
(5) Infiltration in Relation to Evapotranspiration
Harry F. Blaney (Chairman) José Garcia Montes L. K. Sherman
Colin A. Taylor Walter N. White
(6) Infiltration in Relation to Surface-Runoff
Howard L. Cook (Chairman) G. A. Hathaway R. A. Hertzler
W. W. Horner W. B. Langbein

The recent reorganization of the Committee into Sub-Committees, as above outlined, has been of such late development that Sub-Committees for the most part are still in the process of organization and the development of their activities. To a considerable extent during the past year, war-

time activities have had precedence over the regular research-activities of many members of t Committee. In some instances, these war-time activities are of a nature such that a discussion of them is best left to some future date. Despite these limiting conditions, however, much progress has been made by a number of the Sub-Committees and even where not indicated herein, because tangible results have not as yet been obtained, it should nevertheless be recognized that the considerable correspondence within the various Sub-Committees has of itself been productive, particularly in developing lines of thought and courses of action that are deemed to be most effective.

An example of this is the work of the Sub-Committee on Infiltration and the Physics of Soil-Moisture and of the Infiltration-Process. This Sub-Committee has its plans well formulated for its action during the ensuing year, which will center primarily around the preparation and discussion of the paper by its Chairman. In a similar manner, the other Sub-Committees are reaching decisions as to the specific items of work which will be given attention during the ensuing year.

Progress has been made in the extensive study of ground-water, particularly in relation to the war-time activities in parts of Illinois, by the Illinois State Water Survey Division. In this broad study there has been included an investigation of the rate of infiltration in the land-surface above the aquifer. While the data thus far obtained indicate large differences in infiltration upon various parts of the area, there is no evidence as yet as to whether a general improvement in the rate of infiltration over the aquifer would result in an accretion to ground-water. It is recognized that some of the additional water entering the ground as a result of improved soil-treatment and management at the surface may be intercepted by vegetation. Further studies now being inaugurated are designed to ascertain how much of such additional water passes below root-zone, the seasonal distribution of such movement and its relation to rainfall, and similar factors.

A refreshing viewpoint on ground-water recharge is that of S. W. LOHMAN [Trans. Amer. Geophys. Union, Part II, p. 417, 1943] who, in commenting on work in the Wichita Area, emphasizes "the importance of basing quantitative estimates in alluvial areas recharged solely by local precipitation, upon ground-water storage and recharge-facilities, rather than upon underflow, which, as in the Wichita Area, may be rather insignificant as compared with the rate of withdrawal."

WHITE notes that preliminary analysis of data from studies in the Houston (Texas) Area indicates that a high proportion -- perhaps as much as 25 per cent -- of the rainfall may penetrate to the water-table in most years. He also notes that from studies on the Texas High Plains "we reached an average figure for specific yield of 14.5 per cent in the 1,000 square miles of the Plainview Well Irrigation District, and 14.1 per cent in the 450 square miles of the Hereford Well Irrigation District. These figures were based on the decline of water-levels produced by known amounts of pumping in 104 observation-wells during 1938, 1939, and 1940. Wells entirely outside of the pumping districts showed no material change in water-levels during the tnree years and therefore it seemed safe to assume that the decline was caused entirely by the pumping. From our figures it is computed that 1941, a wet year, 4.97 inches reached the zone of saturation in the Plainview District and 3.8 inches in the Hereford District. The precipitation at Plainview that year was 34.35 inches or 12.8 inches above the average, and 34.01 or 12.04 above the average at Hereford. In years of average or below average rainfall, infiltration into these areas is only a fraction of an inch.

"Last year WILLIAMS under the direction of LOHMAN reached an average figure of 30.2 for specific yield based on laboratory determinations in the Wichita (Kansas) Well-Field. With this figure and pumpage and water-level observations he computed the average recharge as 30 to 35 per cent of the rainfall. S. F. TURNER of the Ground Water Division should have some interesting figures this fall on infiltration from streams in the Gila Valley, Arizona."

LEWIS notes in the report of the Sub-Committee on Infiltration in Relation to Irrigation (see Appendix A) that experience during the past season with irrigation of some 20,000 acres, shows the infiltration-problem is an extremely important one in irrigation. Various specific phases of the problem are indicated in this report and the need of further work is indicated,

Applications of organic matter and of gypsum to soils, which, because of high sodium content, have low infiltration-rates, are being tested at several laboratories.

BLANEY and the members of the Sub-Committee on Infiltration in Relation to Evapotranspiration (see Appendix B) are directing their attention primarily upon three problems: (1) The effect of evapotranspiration on infiltration; (2) the effect of evapotranspiration on the quantity (or proportion of infiltrated water) penetrating below the root-zone; and (3) the effect of vegetative cover on evapotranspiration and the rate of entry of water into soils.

The Sub-Committee on Infiltration in Relation to Runoff notes that because of the war the Committee has little to report in the way of new findings. However, it is shown that this period of war can be utilized to good advantage by taking stock of available information and outlining important studies that should be undertaken in the post-war period. Some of the researches that should be planned now are:

(a) Studies of subsurface flood-runoff
(b) Determination of the infiltration-characteristics of all major soils by the use of artificial rainfall
(c) As a basis for (b) above, the development of better techniques and apparatus as well as studies to determine the relation between infiltration determined by such methods and infiltration resulting from natural rains
(d) A determination of the effects of antecedent rainfall and soil-moisture upon infiltration at subsequent storm-periods
(e) Development of better methods of calculating surface-runoff by the use of infiltration-data

The Sub-Committee places as the most important development during the past year an increasing recognition of the importance of subsurface-runoff in flood-flows and consequently an increasing appreciation of the limitations on the infiltration-theory of runoff. But along with this is developing a greater confidence in this theory for the calculation of surface-runoff; for it becomes clearer that what appeared in the past to be failures of the theory often grew out of its misapplication and were not chargeable to fundamental error in the theory itself.

U. S. Soil Conservation Service,
Washington 25, D. C.

APPENDIX A--REPORT OF THE SUB-COMMITTEE ON INFILTRATION IN RELATION TO IRRIGATION

M. R. Lewis, Chairman

Experience during the past irrigation-season with irrigation of some 20,000 acres of guayule in three rather widely separated districts in the State of California, has confirmed my feeling that the infiltration-problem is an extremely important one in irrigation. It is obvious that on heavy soils with a high silt- or clay-content, low infiltration-rates may be expected, but we have found on this Project considerable difficulty in securing adequate penetration of irrigation-water on sandy loam-soils which appear to be of rather open texture. In some instances the difficulty is due to a somewhat compacted clay-pan, but in other instances the difficulty seems to be in so-called "slicking" of the furrows. We very much need more definite information as to just what takes place. We also need further information as to the real values of different types of subsoiling in attempting to increase infiltration-rates.

The question of length of run is of course very closely tied in with that of infiltration-rates. It appears that the change in infiltration-rate as the period of irrigation goes on is of major importance in this connection. We have found that many farmers and field-irrigators prefer much longer runs than we think are justified. We must confess, however, that our information is very sketchy. Much more work is needed along this line.

A good deal of investigation of the problem is going on in various western States but much of it is in the nature of field-observations with little detailed study.

MARTIN R. HUBERTY and ARTHUR F. PILLSBURY published a paper [Proc. Amer. Soc. Hort. Sci., vol. 42, pp. 39-45, 1943] entitled "Solid, liquid, gaseous phase relationships of soils on which avocado trees have declined." In the main, the soils have a shallow, highly permeable A-horizon and a compacted B-horizon. Differences in infiltration capacity between the A- and B-horizons for one soil was in excess of 5000 to 1.

Additional laboratory studies on permeability of soils to water are being made by PILLSBURY and APPLEMAN.

Studies of the effect of the "non-cultivation" orchard practice on texture, structure, infiltration-capacity, etc., are being made by PILLSBURY.

Factors influencing the production and reduction of plow-pan, and its influence on water-penetration into soils, are being studied.

GERALD E. CHRISTIANSEN of the United States Regional Salinity Laboratory reports that experiments were made in the Coachella Valley to determine the effect of organic matter and gypsum in improving the rate of infiltration and depth of penetration where the low infiltration-rates were believed due to the high percentage of sodium of the irrigation-water (about 85 per cent). Improvement was obtained with both organic matter and gypsum, but even more pronounced improvement seemed to result from a thorough drying of the soil as a result of transpiration.

Soil-moisture contents were determined by M. R. HUBERTY for various suction-values within the range of pF to 1.9 (0.89 cm of water). The data indicated, and field-observation confirmed, that heavy storms or heavy applications of irrigation-water caused the moisture-content of the surface-soil to remain in excess of field-capacity for a considerable period. Under these conditions there would be little opportunity for gas-exchanges in the surface-soil, the soil most favorable for root-activity. He also reports that further studies of the effect of the non-cultivation practice in orchards on texture, structure, infiltration-capacity, etc., are being made by PILLSBURY. Factors influencing the production and reduction of plow-pan and its influence on water-penetration into soils are being studied. Studies have been continued on the problem of the effect on infiltration-capacity of applying large amounts of ammonium sulphate to the potato fields of Kern County. Wherever low infiltration-rates have been found on Hesperia sandy loam-soil, ammonium was found to represent a high percentage of the base-exchange complex. The application of gypsum to the potato fields of this area is now almost a universal practice.

In connection with the Central Valley Project of California, an investigation was started early in 1944 to determine the feasibility of recharging ground-water supplies in certain areas in the Upper San Joaquin Valley by water-spreading. The work includes field- and laboratory-determinations of the rates of infiltration of surface-soils and permeability of subsoils. Field-plots are being given different surface-treatments and it is hoped that ways will be found to increase the infiltration-rate in water-spreading areas. The study is being carried on jointly by the Soil Conservation Service, the Bureau of Reclamation, the State of California, Regional Salinity Laboratory, Kern County Water Storage District, and the Edison-Arvin Water Storage District.

Ministerio de Obras Publicas,
Caracas, Venezuela

APPENDIX B--ANNUAL REPORT OF SUB-COMMITTEE ON INFILTRATION IN RELATION TO EVAPOTRANSPIRATION

Harry F. Blaney, Chairman

One of the first objectives of this Sub-Committee, since it was appointed in 1943, has been to review data that might be available on infiltration in relation to evapotranspiration. In this connection progress has been slow because published information on the subject is scattered and the members of the Committee have been busy in war-work and other activities. The extent of future activities of the Committee will be determined by the time its members may be able to devote to the work.

It may be difficult to obtain tangible facts or actual data on some phases of infiltration in relation to evapotranspiration. A partial review of the literature indicates that for the purpose of preliminary discussions, the Sub-Committee should concentrate on the following topics:

(a) The effect of evapotranspiration on infiltration-capacity
(b) The effect of evapotranspiration on the quantity (or proportion) of infiltrated water penetrating below the root-zone: (1) Precipitation; (2) irrigation; and (3) water-spreading
(c) The effect of vegetative cover on the rate of entry of water into soils

Papers and discussions in the Transactions of the American Geophysical Union and investigations by the United States Forest Service and Soil Conservation Service provide some material on these topics. In reviewing Part II of the Transactions of the American Geophysical Union of 1943, the Chairman found the following papers throw some light on the subject of infiltration in relation to evapotranspiration:

(1) Some recharge-phenomena of a Wasatch Plateau Watershed, A. R. CROFT and RICHARD B. MARSTON (Fig. 2, p. 462). The statement on page 464, as follows, is significant:

"Moisture in the upper 36 inches of mantle reached a seasonal low of 16 per cent on September 15 which is two per cent below the calculated wilting-coefficient. This is probably about as

low as transpiration and evaporation can reduce the moisture-content of this soil during the average season.

"Recharge of the mantle began September 24 as a result of snow which melted slowly enough to permit complete infiltration of water into the mantle. Owing to almost complete stoppage of transpiration, and reduction in evaporation during the cool and often stormy days in fall, it is probable that rain or melted-snow water that penetrates the mantle after the middle of September are about as effective in watershed-recharge as equal amounts of water released from melting snow the following spring."

(2) Infiltration-capacities of some plant-soil complexes on Utah Range Watershed-Lands, by LOWELL WOODWARD (Fig. 1 and conclusions, p. 472).

(3) Determination of the effects of watershed-management on mountain streams, by C. L. WICHT. On page 607, C. R. HURSH states, in discussing this paper: "Here arises the question of what type of vegetation will maintain favorable infiltration and ground-water storage with the least water-requirement."

(4) A method of hydrologic analysis in watershed-management by P. B. ROWE (pp. 637, 638, and 640). In a discussion, page 647, R. L. STEVENS states:

"Very good estimates of storage-capacities can be obtained from observed data of rainfall and runoff by determining the storage-capacity of the soil-mantle at the time of a flood-producing rain through evaporation and transpiration during the interstorm periods.

"The degree to which increases in infiltration-capacities are effective in reducing flood-runoff is dependent upon the ability of the watershed to retain the additional infiltrated precipitation. The possibility of increasing the ability of a watershed to retain infiltrated precipitation is limited to the ability of watershed-management programs to either increase evaporation and transpiration, thus making available at the time of flood-producing rainfall a greater portion of the existing storage-capacity, or to increase the storage-capacity of the soil-mantle by increasing its total depth."

L. K. SHERMAN reports results of studies on infiltration-capacity curves which should prove useful to the Committee. In recent correspondence, he states:

"Following are observed facts:

"(1) A complete infiltration-capacity curve, for a long storm, starting with a dry soil, will have a high rate of infiltration-capacity (f) at first; the rate gradually decreases as the soil-moisture increases and finally terminates in a practically horizontal line of constant infiltration-capacity (f_c).

"(2) The drier the initial soil-moisture, the higher will be the starting value of infiltration-capacity (f_c).

"(3) For a given soil type, in a given season, f_c varies with the cover.

"(4) When the soil is wet, f_c is at a minimum constant rate of infiltration-capacity.

"(5) f_c is lower in the dormant season.

"At present we have little knowledge of the relation of the f-curve to the variation of moisture in the soil-profile. What is the relation of f_c to the soil-profile or its moisture-content?"

A paper entitled "Infiltration and the physics of soil-moisture", by L. K. SHERMAN, was presented at the American Geophysical Union meeting at Berkeley, California, on February 15, 1944. SHERMAN called attention to the fact that approximations and short cuts are needed in applying the infiltration-principle to engineering or agricultural works and that reliable approximations require a thorough knowledge of all basic and scientific facts; also that some engineers and hydrologists have dealt with infiltration as surface-phenomena. They have generally overlooked the pertinent relations developed by agronomists and others in soil-science and the physics of soil-moisture. The agronomist deals mainly with the withdrawal of capillary water by plants, etc. Infiltration is the reverse. It deals with the phenomena of supply.

A review of recent literature indicates that there is a difference of opinion in regard to certain phases of the infiltration-phenomena. Thus, for the purpose of clarification and discussion, it is suggested that the Sub-Committee endorse the following concepts of infiltration, porosity, and moisture in the soil-profile as stated by SHERMAN in his paper:

". . . . Consider a column of the soil of one square inch at the surface and extending down d inches into or through the zone of aeration. Assume that this soil has a non-capillary porosity of 30 per cent. The soil-column is thus penetrated by channels, capable of carrying gravity water, through the soil. These channels extend not only downward, but also laterally

in all directions. These channels are constricted at numerous points, but infiltration-water finds its way downward through the lines of least resistance. In each cubic inch of soil, there is an average of 0.30 cubic inch of these non-capillary channels. If d = 20 inches, there would be capacity for six cubic inches of water.

"The soil-column, which is penetrated by these larger gravity-water channels, is filled with small capillary pore-spaces. This capillary porosity of, say, 25 per cent, has a stronger avidity for water than for air. The force of capillarity acts in all directions and it frequently exceeds the force of gravity. Capillary water always moves from the wet spaces toward the drier spaces in accord with well-established laws relating to capillary potential.

"In the surface-layer, of about six inches, when the soil is dry, infiltration enters the soil not only through the larger gravity channels, but also through direct capillary action over the entire surface. This surface capillary movement decreases as the water penetrates deeper. The capillary potential declines so that capillary intake of surface-water proceeds at a slower rate. The water in the gravity channels, however, continues to penetrate deeper and at a fairly uniform rate. This gravity water now furnishes a supply at relatively high potential, for lateral capillary absorption into the soil. The gravity channels are the water mains and the capillary pores are the local-supply feeders.

"Suppose that infiltration has been furnished at capacity-rates for three hours and is then stopped. It is found that water has penetrated to a depth of 20 inches, then this condition exists: At the surface the soil has been subjected to a three-hour supply-period for capillary absorption. At depth of 20 inches the soil has just begun to have an additional supply of capillary moisture. At about ten inches, or mid-depth, the soil has had a one and one-half hour period for the supply of additional capillary moisture.

"Though the supply of further infiltration was stopped at the end of three hours, the gravity channels are full of water. Capillary action continues to draw upon this gravity water until the capillary pores are all filled or until the gravity storage is gone.

"A word here on the phenomena of f_c or ultimate constant infiltration-capacity. Normally the soil just below the zone of aeration, or the root-zone, holds 100 per cent of water in its capillary porosity. It is below the effects of evaporation or transpiration. No capillary water is lost through gravity. It may be lost, in part, by upward capillary movement into the root-zone. However, this is commonly offset by new supplies from rainfall. When infiltration penetrates down from the surface to this sub-strata and when a sufficient time-interval exists, then all of the capillary porosity, from the surface to the aforesaid sub-strata, will be filled. Infiltration will continue without any abstraction by capillary action. The rate of infiltration will be constant. The condition of f_c exists."

Relative to topic (b), the effect of evapotranspiration on the quantity (or proportion) of infiltrated water penetrating below the root-zone, there are many data available in some areas that should be carefully analyzed. As early as the end of the 18th century so-called drain-gages, later known as lysimeters, were used to study the movement of moisture in soils. DALTON is credited with being the first to install lysimeters. One of the questions was to find out how much precipitation percolated through the soil to the ground-water.

WALTER N. WHITE and S. F. TURNER report that the studies of evaporation and transpiration by the United States Geological Survey in Safford Valley, Arizona [Trans. Amer. Geophys. Union, Part III, p. 738, 1941] were continued during 1943. Also that a new station was started with 29 tanks. These tanks range from four to ten feet in diameter and the vegetation consists of baccharis, salt-cedar, and cotton-wood saplings. Other agencies have conducted soil-moisture and lysimeter-studies in various areas in the United States and other countries.

For many years the Division of Irrigation, Soil Conservation Service, has conducted field-, lysimeter-, and tank-studies to determine evapotranspiration. Rainfall-penetration studies were made by BLANEY, TAYLOR, and YOUNG for several years in southern California [see California State Bull. 33, 44, and 46]. Recent drainage-studies in Imperial Valley indicate that evapotranspiration, as well as permeability, is a major factor to consider in the design of sub-surface tile-drains for irrigated lands.

MAURICE DONNELLY, United States Soil Conservation Service, Citrus Experiment Station, Riverside, California, submitted the following statement:

"In connection with water-spreading operations, the following hypothesis is advanced by the present writer: 'Given a soil in which the permeability-rate is a function of macropores (non-capillary pores) which in turn depend chiefly on aggregation of soil particles, rather than on openings between single-grained coarse particles, optimum conditions for permeability in such a soil can be maintained only if the soil is periodically dried out. The only

feasible method for drying out such a soil is by the use of growing plants having close-spaced root-systems that permeate the soil-mass. Somewhat less than optimum conditions can be maintained without growing plants if the water is applied at intervals spaced long enough apart to permit the soil to drain to moisture-content approximately equal to the field-capacity. If water is applied continuously, or if applied at intervals so close that there is not enough time for the soil to drain to the field-capacity, all of the soil, or part of the soil, may be wetted to such a degree that there will be a gradual reduction in the number and size of the macropores that depend on soil-aggregation. If a zone of soil is continuously wetted for long periods to a moisture-content higher than the field-capacity it is possible that a physical state will be brought about resembling that of a clay-pan. Such a false clay-pan is not due to the eluviation-illuviation process.

"Winter cover-crops are generally grown in California citrus orchards. As now viewed, the purpose of cover-cropping is to prevent erosion from winter rains and to maintain a soil-structure that will permit the ready ingress of irrigation-water. Where citrus soils are tilled over a period of years and no cover-crop is grown, the rate of penetration of irrigation-water into some soils is greatly reduced.

"As observed by E. R. PARKER, HANS JENNY, and others, there are indications from citrus fertilizer-plots at the University of California Citrus Experiment Station that some commercial fertilizers affect soil-structure in such a way that infiltration-rates are appreciably reduced. DANIEL G. ALDRICH of the Citrus Experiment Station has recently become engaged in a study of the effect of addition of commercial fertilizers on soil-structure, particularly in relation to infiltration and permeability.

"YOUNG and BLANEY reported in 1942 on the consumptive use of water by native vegetation in California. Coupled with the recent study of rainfall-distribution by the present writer, these data on consumptive use indicate that in periods when rainfall is near the mean in seasonal total and follows the so-called 'normal' pattern, little runoff or additions to underground storage can be expected in lowland areas in southern California from rain falling on soils that are well covered by low-growing vegetation. The studies emphasize the need for distinguishing the manner of rainfall-distribution as well as the total seasonal amount. Thus, judging by the data of YOUNG and BLANEY, water from rains of 1928-29 would have been largely consumed by such vegetation where it existed. In that year (1928-29) the rainfall totalled some 12 to 14 inches in lowland southern California and the distribution was near that of the 'normal.' Conversely, in 1935-36, when the total rainfall was again some 12 to 14 inches, the distribution was in the form of an 'elongate peak' with more than half of the rain coming in February, 1936. A large proportion of the total fall in this month was converted to runoff, or penetrated below the root-zone. For the past ten years in southern California, rainfall, runoff, and penetration of precipitation below the root-zone have been high. When the cycle again shifts to drier years, YOUNG and BLANEY'S data should furnish important guides on the conservation of water by control of non-economic vegetation, especially on soils where the macropores are in large measure set up by openings between coarse rock-particles."

In some instances there is a difference of opinion among research-workers, hydrologists, and engineers as to the use of certain terms and definitions relating to infiltration and evapotranspiration studies. The Sub-Committee will include a study of this problem in its program for the coming year.

Los Angeles, California

REPORT OF COMMITTEE ON PHYSICS OF SOIL-MOISTURE, 1943-44
(The role of the pF in the dynamics of soil-moisture)

F. J. Veihmeyer, Chairman

The membership of the Committee is as follows:

Dr. L. D. Baver, North Carolina State College, Raleigh, North Carolina
Dr. G. B. Bodman, University of California, Berkeley, California
Dr. Richard Bradfield, Cornell University, Ithaca, New York
S. J. Buchanan, United States Waterways Experiment Station, Vicksburg, Mississippi
Dr. T. F. Buehrer, University of Arizona, Tucson, Arizona
Dr. I. A. Denison, National Bureau of Standards, United States Department of Commerce, Washington, D. C.

Dr. N. E. Edlefsen, University of California, Davis, California
Dr. Willard Gardner, Utah Experiment Station, Logan, Utah
Dr. Glennon Gilboy, Massachusetts Institute of Technology, Cambridge, Massachusetts
Dr. O. W. Israelsen, Utah State Agricultural College, Logan, Utah
Dr. L. B. Olmstead, Bureau of Plant Industry, United States Department of Agriculture, Washington, D. C.
Dr. L. A. Richards, Bureau of Plant Industry, United States Department of Agriculture, Riverside, California
E. A. Willis, Bureau of Public Roads, United States Department of Agriculture, Washington, D. C.
Dr. F. J. Veihmeyer, University of California, Davis, California

The annual report of the Committee is a discussion of the use of the term pF in soil-moisture investigations. SCHOFIELD [Trans. 3rd Internat. Cong. Soil Sci., vol. 2, pp. 37-48, 1935] defines the pF as follows:

"The pF is the logarithm of BUCKINGHAM'S potential. By analogy with SORENSEN'S acidity-scale the symbol p indicates its logarithmic character, while the symbol F is intended to remind us that by defining pF as the logarithm of the height in cm of the water-column needed to give the suction in question, we are really using the logarithm of a free-energy difference measured on a gravity scale. By basing our scale on free-energy rather than pressure, we are not troubled in our calculations by the influence of pressure on the density of water".

Measurements of soil-moisture usually are made with one of two objectives: Either to determine the mass of water per unit-mass of soil; or the tightness with which it is held by the soil. Usually we want to know how much the soil contains, how much is available for plants, and how long it would last before it would be depleted. If the relationship between the free-energy of the moisture in the soil and the moisture-content has been found, then, of course, the determination of one fixes the value of the other.

Dr. WILLARD GARDNER commented last year [Trans. Amer. Geophys. Union, p. 411, 1943] on the use of the logarithm of the free-energy of soil-moisture. He has prepared the accompanying statement (see Appendix A) for the purpose of stimulating discussion. His statement was sent to each member of the Committee and to a selected list of investigators with a request for their comments, opinions, and criticisms concerning the use of the pF-concept either as to its significance in the dynamics of soil-moisture, or as it is being used to designate the physical state of water in the soil, the moisture-contents being reported as pF rather than mass of water per unit-mass of soil. GARDNER'S statement and the replies received are published verbatim without being edited by the Chairman. In a few cases a part of the material received which was not pertinent to the discussion was deleted.

University of California,
Davis, California

APPENDIX A--THE ROLE OF THE pF IN THE DYNAMICS OF SOIL-MOISTURE

Willard Gardner

The pF-concept has no doubt served a useful purpose and has found its way permanently into the literature of soil-physics. It should be noted, however, that the gradient of the function, p/ρ, (or the gradient of $\int dp/\rho$ for compressible fluids) enters explicitly into the classical literature of hydromechanics, whereas the other terms in the free-energy (better, thermodynamic potential) are but remotely involved. The logarithm of $\int dp/\rho$ likely does not appear at all.

BAVER has presented interesting data from which he shows that the percolation-rate of the soil is correlated with a porosity-factor defined as the ratio of the non-capillary porosity to the pF of the flex-point. Both these quantities are determined primarily by the configuration of the void-space in the soil, but the permeability is likewise dependent upon the geometry of the void-space, and it is to be expected, therefore, that these two physical quantities should be correlated.

However, the POISEUILLE equation may be written

$$v = -(a^2/8\mu\rho)\nabla\Phi \qquad (1)$$

in which a is the radius of the tube, Φ the potential function, μ the coefficient of viscosity, and ρ

the density of the fluid, and it would seem that there should exist a soil-parameter, a, having the dimensions of length that could function as an effective radius of the soil "channel", and in that case, DARCY'S law would include the POISEUILLE equation as a special case.

The tension at the air-water interface may be expressed

$$T = 2\sigma/r \tag{2}$$

σ being the surface-tension and r the radius of curvature of the interface. The "free-energy", F, for incompressible fluids may be expressed in the form

$$F = (2\sigma/\rho r) \tag{3}$$

and if we define a function, k, thus

$$k = (\sigma^2/2\mu\rho F^2) \tag{4}$$

in which F is the free-energy at the flex-point, and introduce the radius of curvature, r, by means of (3), we obtain

$$k = (4\sigma^2/\rho^2 F^2)(1/8\mu/\rho) = (r^2/8\mu/\rho) \tag{5}$$

and, because of the POISEUILLE equation, it seems likely that this "porosity-factor", k, should be linearly, positively, and highly correlated with the permeability, provided the free-energy at the flex-point has appropriate significance.

Although there may be many problems in soil-physics in which the free-energy appears naturally, it seems a little far-fetched to introduce thermodynamic functions into problems of mechanics, and still more so in suppressing the physical concept itself by referring constantly to its logarithm. Plotting the free-energy (capillary potential, pressure-potential, stress-potential) in terms of the moisture-content of the soil on semi-logarithmic paper would accomplish essentially all that is accomplished in defining the pF, and it is possible that SCHOFIELD may have had nothing more in mind when he suggested it.

It is true that the pH has assumed great importance in chemistry, but it would seem awkward to introduce the logarithm of mass, momentum, energy, moment of inertia, etc., into problems of mechanics.

It is hoped that what is said above will be regarded as wholly constructive. It is prompted by a desire to be helpful.

Utah State Agricultural College,
Logan, Utah

DISCUSSION

ALFRED B. C. ANDERSON (University of California)--Dr. GARDNER seems to be of the opinion that it is a little far-fetched to express the physical concept of free-energy by referring to its logarithm expressed by pF. I am of the same opinion and also feel that the time is suitable for a recrystallization of our conventions for the representation of the energy of soil-moisture.

It is stated frequently of mathematics that it is a universal language. This is probably true except for a few instances that come to mind where a limited realm of science occasionally adopts its own peculiar nomenclature and terminology differing from that current in mathematics as a whole: In chemistry, the use of pH instead of log (1/H); in electronics and electrical engineering, the use of the symbol j in place of the conventional symbol i to represent $\sqrt{-1}$. These changes are well justified, but not so it seems the introduction into soil-science of pF (in place of log F or even just plain F) either on the basis of logic or of utility.

Soil-moisture may have either a positive or a negative free-energy whose value would depend upon the datum chosen. It would seem to follow, on the basis of the pF-terminology, that we will have the logarithm of negative as well as positive free-energies. It is clear to all what the logarithm of a positive quantity is, but it is not so, what the logarithm of a negative one is. It is in fact a complex number, which in general involves both a real and an imaginary number, as any test on

the theory of the complex variable will show. If we are to maintain any semblance of logical mathematical consistency in the use of the symbol pF, we must get around the mathematical fact that the logarithm of a negative free-energy is a complex and not a real quantity. It is hard to accept and to attach any physical significance to the idea of the energy of soil-moisture being represented by a complex quantity. Clearly, then, as pF has been usually defined and used, we are led into insurmountable difficulties of logic. The whole thing could easily be cleared up by an amplification of our conventions as to what to do in soil-science with the logarithm of negative energies. If we are to do this, it seems to me, then why not deal with the logarithm directly instead of clothing it in the veil of pF, which symbol is apt to give the impression to a student that some new fact or property comes to light or that something different is involved than is given by log F or even F. GARDNER'S suggestion of dealing with the free-energy directly, and then plotting the free-energy on semi-logarithmic paper when it is desirable to show a great range of free-energy values seems practicable. The elimination of pF from continued use in the literature of soil-physics would appear to result in an improvement in clearness and ease of treatment of soil-moisture energy-relations.

One wonders why no attempt or suggestion has ever been made to express the energy of soil-moisture in other forms besides log F. It might seem far more desirable to express the energy in the form of $\sinh^{-1} F$, that is, the hyperbolic arc sine of the free-energy, or in the form of tanh F, that is, the hyperbolic tangent of the free-energy of the soil-moisture. Both of these well-known and established functions have the desirable property in common with log F of contracting the energy-scale for large values. Besides, they do not lead to the same confusion as with the logarithm arising in the representation of both positive and negative energies. They are not uncommon functions. Almost any book of mathematical tables containing logarithms will include the hyperbolic functions.

It seems clear that the free-energy of the flex-point on a logarithmic curve will have the same value as for a curve plotted directly in terms of F. The "flex" will, however, be more pronounced in the latter case. The flex-point will also appear at the same energy-value if we plot the curve in terms of $\sinh^{-1} F$ or tanh F. There would seem, therefore, to be no valid reason for correlating the flex-point of log F instead of just plain F with moisture-properties. Plotting the energy in terms of pF or log F instead of F has the apparent effect of making discordant values of F seem to agree closer than they really do.

By a most surprising coincidence the symbol pF has another totally different meaning from that current in soil-physics. Only a short time ago it was advocated that the original connotation of pF, as customarily used for describing the energy of soil moisture, should be eliminated [see 3 of "References" at end of discussion]. The arguments against using the symbol pF for representing moisture-energy seemed reasonable. In place of the energy-connotation of pF, however, it was suggested that a totally different meaning be substituted. It was suggested that the symbol pF should represent the very small unit of electrical capacitance quite generally called the micromicrofarad in electronics but occasionally outside of the United States called the picofarad. pF is the abbreviation of the latter. The proposal arose as a result of an article by two of us dealing with the electrical capacity of the two-electrode plaster of Paris block as an indicator of soil-moisture content [2]. The seeming undesirability of assigning another totally different meaning in soil-science to the well known symbol pF was pointed out later [1] in another article.

It hardly seems true that the term $(P/\rho) = vdP$ is the only term in classical hydrodynamics that enters into free-energy. What about the gravitational and adsorptive field-potentials as well as the surface-tension and osmotic potentials so-called? This raises the question about what is really meant by the word free-energy. There is the very special definition originally involved in the definition of pF [5,6] in connection with the freezing-point depression of soil-moisture. This was based on the length of a column of water in equilibrium with the soil-moisture. This is not free-energy in the accepted sense as defined either in thermodynamics, physics, or chemistry [see 4, articles 21, 44, 62, and others] and it would seem to me has a limited usefulness. Is this definition implied in GARDNER'S article? Possibly not.

It has been proposed elsewhere [4] to introduce the commonly accepted definition from thermodynamics, into the field of soil-science. By so doing a student already trained in the fundamental physical sciences such as chemistry and physics should find little trouble in mastering the energy-relations occurring in soil-moisture. He can then, with a minimum of change and confusion, carry over bodily into soil-studies the energy-relations already learned and developed in the thermodynamics of his courses in physics and chemistry.

The proposal of introducing the commonly accepted thermodynamic definition of free-energy into soil-science was made only after a thorough consideration of all other available forms of ex-

expressing the energy [see 4, article 44, p. 146, and others]. This definition makes it possible to treat the most complicated problems that might arise in the movement and equilibrium of moisture. Ways used hitherto for expressing the energy of soil-moisture are not comprehensive enough to treat the energy of moisture in all its possible coexisting forms. The thermodynamic definition includes the properties of all the different soil-moisture potentials used in the past as special cases. It goes further, and makes possible the treatment of changes in the energy of soil-moisture caused by changes in temperature [see 4, articles 72 to 81].

The thermodynamic definition of free-energy enables one to treat the equilibrium and movement of water of crystallization in a salt, water present and interpenetrating a colloidal crystal lattice such as in bentonite and soil colloids, water containing dissolved material, water frozen, water in a gravitational field or adsorbed on the surface of a colloidal particle, water in the vapor-form, water flowing with a given velocity, and water at rest. It makes possible the treatment of the forces involved in the movement of moisture from the soil through the plant-roots and up the xylem to the leaves of the plant, finally to be transpired through the stomata into the atmosphere.

The question is frequently raised by some who are not fully conscious of the distinction between thermodynamic equilibrium and mechanical equilibrium that the thermodynamic concept of free-energy is not adaptable to processes involving any bodily movement of the moisture since, as they say, thermodynamics treats only systems in equilibrium. A system may not be in mechanical equilibrium and yet be in thermodynamic equilibrium. In fact the kinetic energy of soil-moisture should also under certain conditions be included as one of the components of the total free-energy. This has more or less been merely stated but not adequately justified in article 82 of reference 4.

Since so many forms and ways of expressing the energy of soil-moisture have arisen in the past, enough to bewilder any new student (and there will be many of them after the war who must get their additional education in a hurry), I suggest, as before [4], that we adopt the thermodynamic definition used extensively in physics and chemistry for describing the energy of soil-moisture with one minor change. This involves the use of f instead of F since F in chemistry refers to the free-energy per mol of a substance. On the other hand, in dealing with moisture in its various forms, it appears more convenient to deal with the free-energy per unit-mass, which we call f. This is no arbitrary convention as the usual thermodynamic convention in chemistry is to represent specific quantities by small letters. All the conventions are well established [see 4, article 10], and any student of soil-science in the future probably will be acquainted with them from his physics and chemistry before he begins his study of soil-physics.

In the article by GARDNER a slight objection seems to be raised against using the words "free-energy" instead of the words "thermodynamic potential". The reason for using the words "free-energy" has been taken up in detail in article 44 of reference 4. It is based primarily on agreeing with the prevailing conventions established in the literature. The aim in reference 4 was to develop the thermodynamics of soil-moisture in such a language and symbolism that students would encounter a minimum of changes, confusion, and difficulty in carrying over the body of thermodynamic relations learned in physics and chemistry. The "free" in free-energy refers, of course, to the maximum amount of mechanical and electrical work that can be "freed" when the system passes isothermally from one state to another. It is the energy that is free and available for mechanical and electrical work. Only when the system passes reversibly from the initial to the final state can all the free-energy be "freed" energy and therefore be obtained as mechanical or electrical energy. In natural processes the actual mechanical or electrical energy obtained is less than the free-energy, the difference being converted into such forms as heat energy.

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VLADIMIR S. ARONOVICI (Soil Conservation Service, United States Department of Agriculture)--The term pF refers to the logarithm of a specific tension applied to the soil. The energy-relationship of the soil to water is measured by pF. Capillary potential is the negative energy which resists this tension. Broadly speaking, the larger the soil-pores the lower the capillary potential. The moisture retained against a series of tensions produces the sorption-curve.

Dr. L. A. RICHARDS of the Regional Salinity Laboratory at Riverside, California, has conducted many comparisons of the moisture-equivalent as determined by the standard method with the moisture retained against one-third atmosphere tension and has found that they check closely. Field-capacity has been found to compare favorably with about 19.5 cm mercury tension. The permanent wilting-range is equivalent to the moisture retained at 15 atmospheres tension. The equipment required for determining the field-capacity and moisture-equivalent by the tension-method is relatively simple and far less costly for limited work than the centrifuge. Further, the sorption-curve reflects the character and distribution of the soil-pores. It is probable that determinations of frequency and amount of irrigation may be guided more accurately when an analysis of these sorption-curves and the hysteresis-effect are more thoroughly understood. It is also probable that a relationship between the character of the sorption-curve and permeability can be developed that is sound for all localities. At present none of the proposed techniques produce sufficient conclusive evidence.

In areas where a water-table is at a depth of less than six feet and is subject to fluctuation, the moisture-holding capacities are likewise fluctuating. To conduct moisture-studies in such areas, close coordination of water-table position as determined by piezometers with predetermined sorption-curves of the soil above is necessary. There is much room for further study along this particular line of endeavor. The use of tensiometers in the field is a direct method of measuring the soil-water energy-relationship in the field. The present limitation of this equipment is the restricted range of tensions measurable.

L. D. BAVER (North Carolina State College)--In discussing problems relating to the retention and movement of soil-water, one can approach the solution purely from the mathematical angle or one can sacrifice some mathematical accuracy in favor of a relationship which lends itself to a more versatile usage. As far as the wide field of soils is concerned, the former approach is usually restricted to a relatively few individuals who have been fortunate enough to have had a large amount of training in mathematics. The latter permits a general understanding of the physical principles involved without becoming lost in a maze of mathematical formulas. It is in this group that the large majority of soils-investigators find themselves.

I believe the pF-concept of soil-moisture has done much to portray the energy-relationships in soil-moisture problems so that investigators can make practical use of them. It has proven to be a useful tool in understanding soils. The pF-curve can be described with considerable meaning in terms of soil-properties. This has not been equally true to date with the moisture-potential curve.

Undoubtedly, the mathematical physicists can render a real service to a better understanding of soil-moisture if and when they can interpret the moisture-potential curve in simpler terms. As GARDNER points out in his discussion, the inclusion of the POISUEILLE equation as a special case in DARCY'S law should make the k-value correlate with permeability and the soil-factors associated therewith.

From a mathematical point of view it remains to be proven whether the moisture-potential curve is a continuous function of the same relations or an overlapping of two or more curves to give what appears to be a continuous function. I am hopeful that mathematical ingenuity will be able to formulate a clear cut expression of the moisture-potential curve in terms of soil-properties that can be measured so that we can take much of the empiricism out of our soil-physics terminology. Until then, we will find that the pF-tool will continue to be the mechanism by which most investigators of soils will handle soil-moisture relationships.

HARRY F. BLANEY (Soil Conservation Service, United States Department of Agriculture)--I think letters, such as pF, to designate a term are confusing. Why not give the term a name in words? Some soil-scientists are studying the relation of pF to wilting-percentage and moisture-equivalent of different soil-types and they may develop a short cut. Perhaps the use of the term pF will cause more engineers to comprehend the significance of energy-relations in soil-moisture problems than the use of potential functions. In my opinion empirical methods are justified in soil-moisture work in connection with irrigation and drainage-field investigations, particularly if their employment will conserve man power or if they are more practical. However, in some instances the use of the logarithmic scale will be less advantageous than that of the linear scale.

RICHARD BRADFIELD (New York State College of Agriculture)--I have found the pF-concept very useful in teaching the physics of soil-moisture. It is a concept which average students grasp a little easier than the free-energy concept and, at the same time, for the student who is properly grounded in physics and mathematics, the transformation to free-energy units can be easily made. By using the logarithm of the tension in cm of water, we can bring all of the various empirical constants at least somewhat in line and show their relationship much better than we could to elementary students before SCHOFIELD'S concept was introduced. I think the complete pF moisture-curve of the soil, plotting pF as the function of moisture-content, affords very valuable data for any soil. It of course varies with structure but as KEEN pointed out such a curve can be used to portray directly or indirectly the pore-size distribution of the soil which is, I think, a very important physical characteristic. I think the pF-concept will stick.

LANNES E. DAVIS (University of California)--The matter of units (or dimensions) is sometimes confusing. Rationally, the dimensions of a potential should be energy per "energy-charge", for example, ergs per gram. (Energy-charges are extensive quantities such as mass, electrical charge, entropy, volume, etc., as contrasted with potential, temperature, pressure, etc.) In practice, rational potentials are frequently divided by the conventional value of the acceleration of gravity, 980 cms/sec^2, so that the result is expressed as a length, that is, in cm. The pF is the logarithm of the potential expressed as a length.

It is frequently difficult to suggest references to the literature for students without elaborate explanations in class. It is almost the exception to find the nature of the potential which is discussed in a paper explicitly stated. A potential may be called a "capillary potential" when it is not clear whether the potential is actually the partial function of the capillary forces, or is in fact a function of capillary forces plus adsorptive or field forces plus osmotic forces. As an example, in BAVER [p. 211, Fig. 48], data obtained by vapor-pressure methods, by centrifugal methods, and by suction against a porous plate are combined into one curve. This is inconsistent since a porous-plate tensiometer is not an osmometer.

Whenever such difficulties are eliminated, the question of whether a potential function should be plotted on ordinary coordinate paper or on semi-log paper, or whether the logarithms of the function should be plotted is a matter of convenience which is not usually disturbing to students. The pF-function has the advantage that it can be plotted readily on ordinary coordinate paper.

The principal issue presented by GARDNER is more fundamental than the preceding comments. However, apparently he has not considered the most fundamental difficulty involved in the use of thermodynamic techniques in the study of soil-moisture problems. In principle, thermodynamics is adapted to the discussion of static problems or of the energy-changes involved in transitions between well-defined, static states of a system. It is not well adapted, theoretically, to the consideration of systems while they are undergoing changes, that is, while water is moving rapidly through a soil. In practice this difficulty is overcome whenever measurements can be taken more rapidly than the changes occur, so that we measure a function of dF, that is, the change in free-energy of the system between two states characterized by the free-energy values F and (F + dF), respectively. Alternatively, we may consider the instantaneous potential-gradient in a soil through which water is moving.

I do not find it "far-fetched to introduce thermodynamic functions into problems in mechanics". The term thermodynamics is misleading; recently BRONSTEAD has preferred the more inclusive term "energetics", which avoids the emphasis upon problems involving heat as a form of energy. Whenever an adequate mechanical discussion of a system would require the description of non-measurable microscopic properties, either statistical mechanics or energetics must be resorted to. However, the theoretical treatment of relations between water-content, water-movement, local forces, configuration of "capillary" and "non-capillary" pores, and so forth, need not be precluded. Such studies have a progressive character, but an adequate or complete description usually is not forthcoming.

Most of the discussion by GARDNER appears to be concerned with permeability as a function of surface-tension, film-curvature, viscosity, and fluid-density. His purpose in presenting this discussion is not quite clear. He states in the first paragraph "the gradient of the function (P/ρ) . . . . . enters explicitly into the classical literature of hydromechanics, whereas the other terms in the free-energy (better, thermodynamic potential) are but remotely involved". The derivatives of "the other terms" vanish, of course, in a saturated system and in this sense are not even remotely involved in such systems. But our attention cannot be confined to saturated systems--in fact they are exceptional cases. On the other hand, it seems doubtful that permeability in the unsatu-

rated state can be exclusively a function of the geometry of pore-spaces, particularly in saline soils, or in montmorillonitic clays, in which cases osmotic forces and field-forces, respectively, may be quite important.

JOEL E. FLETCHER (Soil Conservation Service, United States Department of Agriculture)--In regard to the use of pF and the paper by GARDNER, I am inclined to agree with GARDNER that little if anything can be gained by the use of pF over the simple plotting of the tension on semi-logarithm paper. In addition, in some permeability-work, it would seem that at least for some soils the flex-point would be more strongly defined when the tension is plotted on an arithmetic scale than on the logarithmic scale. Thus the use of pF might actually constitute a disadvantage. In the little work I have done on non-capillary pore-space, the transformation to the pF-scale merely constituted an additional operation with no advantage gained that was visible to us.

ROBERT GARDNER (Colorado State College)--When the pF-symbol was first proposed, I raised an objection to its use on the grounds that it might lead to confusion [Soil Sci., vol. 43, pp. 277-283, 1937]. Since that time, the symbol seems to have appealed to the imagination of workers on soils and is now in such wide use that it appears to be here to stay. However, I feel that there has been some tendency to attach meanings to configurations of pF-curves which have no fundamental significance, and I believe that the action of your Committee in introducing the question for discussion at this time will be of value in defining the limitations of interpretations which can be placed on pF-curves.

R. W. GERDEL (United States Weather Bureau)--From the practical standpoint any controversy between the plotting of a function on semi-log paper and the plotting of the logarithm of the function on rectangular coordinate paper can only end in a draw. The concept of a function is not necessarily suppressed by use of its logarithm.

The tendency to use symbols to designate a function would undoubtedly result in "free-energy" (capillary potential, etc.) being expressed by a new, or existing symbol (such as f or Φ) which to the uninformed becomes as confusing as the term pF. The controversy then has returned to the original starting point, that is whether a single functional index satisfactorily delineates the dynamic principles involved.

During the past five years, the writer on several occasions has applied the pF-flex point phenomena to the practical application of soil-drainage with some success. In dealing with agricultural engineers and agronomists who were not familiar with the term pF, little difficulty was encountered in explaining the term and its significance. The logarithmic function appeared to be as comprehensible as the arithmetic value of free-energy. Recently the development and presentation of a pF-concept for the liquid water-content of a deep snow-pack appeared to be readily understood by a group of hydrologic engineers who were not otherwise familiar with the function.

The present-day trend toward litho and photo-offset reproduction of technical papers requires that charts and graphs be as open and legible as possible since this method of reproduction does not produce as clean, fine lines as type. Logarithmic graphs frequently become illegible when sufficiently reduced to meet the requirements of publication by offset-reproduction. Certainly, any blackboard presentation of capillary-potential soil-moisture curves is more readily accomplished by use of the logarithm of the function than by trying to present the function on a logarithmic scale.

Climatologists, in presenting graphic data dealing with wind-, temperature-, and humidity-gradients have used height as the ordinate on semi-logarithmic paper and the logarithm of height on rectangular coordinate paper. There seems to be no controversial issue involved in this field.

The foregoing criticism is an effort to discuss the practical aspects of the problem of presenting the pF-concept rather than to discuss the technical veracity of the concept which will undoubtedly be thoroughly discussed by others.

NATHAN S. HALL (Michigan State College)--GARDNER has brought to the surface the elements of an interesting subject, namely, whether a term that has as its foundation principally convenience, should be continued or whether the more rigid terms with appropriate units should be used throughout. It seems to me that an analogy between pF and pH will serve well in considering the subject. It is true that many persons use pH blithely, with little regard to its definition--averaging them as if they were coefficients, not exponents. It is not uncommon to see systems compared as being of the same order of magnitude when they differ as little as one pH-unit. At the present, those who find it necessary to translate pH into active normalities and back, have shut their eyes to these abuses and pro-

ceed as if they did not exist. When and where pH is abused in the scientific literature, it reflects on the editors and reviewers of the publication, and in the public press it is accepted as one of the many inaccuracies that occur.

It seems to me that pF will be assigned to a similar rôle. As the concept of the water-tension and pressure in a soil as related to the moisture-content and to tile-depth becomes more widely used, it can easily be assumed that tile-depths will be referred to as "such a pF". Admittedly this is bad usage, but if the temperature is known and the pF given, then the total moisture-potential can be translated into the more rigid terms. If there is a possibility that the concept of the relations between moisture-content and total moisture-potential is going to be used by the majority of the workers in agronomy, research, and extension alike, then a convenient term, as pF, will serve as a convenient go-between and in that event will be subjected to many abuses but under favorable conditions can be translated by those interested into terms that will lend themselves to a mathematical analysis.

If pF is assigned to this rôle, it behooves those instructors who make use of the term to be sure they know the definition of the term and to impress upon their students the limitations of its usage. If this is done faithfully, there need be no fear as to confusion. The editors and reviewers of scientific publications will be able to restrain the use of the term, to keep it within the reasonable bounds and to reduce the abuses to a minimum.

PAUL J. KRAMER (Duke University)--I do not care to comment on the mathematical aspects of the pF-concept of soil-moisture, but only on its usefulness. It is a mode of expressing soil-moisture conditions which seems more useful to the soil-physicist than to the plant-scientist. Expressing the moisture-content of the soil as the logarithm of the potential has limited intrinsic advantage and is less meaningful to most plant-scientists than to report it as a percentage of the dry weight of the soil. Of course neither the pF-value nor the moisture-percentage of a soil is very enlightening by itself, but only becomes so when considered in relation to the field-capacity and the permanent wilting-percentage of the soil. The plant-scientist is usually chiefly interested in the volume of water readily available to plants in a given volume of soil. The best way of expressing soil-moisture probably is as volume of water per volume of soil, but the difficulty of obtaining samples of known volume results in it generally being expressed in terms of the dry weight. Expressing it in terms of pF is usually less useful than the conventional method. If the investigator is studying movement of water in the soil or from soil to plant he can sometimes profitably use some form of the free-energy concept, such as the capillary potential, but there seems to be no advantage in expressing the values logarithmically.

D. P. KRYNINE (Yale University)--The conception of the "capillary potential" is practically not used in engineering applications of soil-physics. Personally, however, the writer is very much interested in this conception, since he feels that all factors which may influence the capillary flow in soils should be carefully examined. The use of semi-logarithmic paper for plotting the values of the capillary potential is convenient, in the same way as, for instance, for plotting the results of a mechanical analysis.

To characterize the geometry of the total void-space and that of the space available for the nonsaturated flow, GARDNER introduces two parameters, a and r [equations (1) and (5)]. It should be noticed that the parameter, r, does not define the geometry of the available void-space satisfactorily. This is because a given amount of moisture (for instance, at the flex-point) bounded by interstices of a given radius r, may be located within an idealized tube of a radius a in an infinite number of ways. Taking into account, however, that a liquid tends to decrease its surface, the most probable location of capillary moisture within an idealized cylindrical tube would be between the two cylindrical surfaces whose radii are a and r, respectively. In mathematical terms, this furnishes an equation connecting the values of a and r, in addition to equations (1) and (5). Furthermore, it is not quite clear to the writer whether the condition $a > r$ always holds in the case of moving capillary moisture. It seems possible that in some occasions the discharge (or at least the velocity) of the nonsaturated flow may be larger than that of the saturated. Analogies from surface-hydraulics (sewers' discharge) suggest this possibility.

G. W. MUSGRAVE (Soil Conservation Service, United States Department of Agriculture)--GARDNER has expressed a point which doubtless has concerned many of us, namely, that by constantly referring to the logarithm pF, we tend to suppress the physical concept involved in many of our problems. From the very little work we have done on the tension at which water is held in a soil, we have received the definite impression that a porosity-factor which correlates positively with permeability is a distinct positivity. Whether or not it will be linear throughout the range of

soils and their widely variable physical condition, we are not so sure, but in any event, it is a most promising field of inquiry. Research in this direction should be stimulated, since the returns from such work may be in terms of large dividends.

M. L. NICHOLS (Soil Conservation Service, United States Department of Agriculture)-- My opinion, from the limited amount of study I have been able to give the subject, is that while pF will probably give us a reasonably accurate measure of moisture, particularly if we can evaluate hysteresis, it is also important in determining rates and amounts of infiltration and factors of permeability, slacking qualities, etc., that is, the general behavior of soils under wetting and drying. The combination of plaster-of-Paris blocks with thermocouples, for example, enables us to tell when freezing occurs.

In general, my feeling is that while the determination of moisture-content is in itself very valuable, there are many other things which are of primary importance in the soil's behavior in relation to water that we should investigate in connection with these studies of pF. We have, therefore, been planning to expand these studies in connection with the very practical objectives of the Service.

ARTHUR F. PILLSBURY (University of California)--The term pF has many limitations, but it has proved useful in reporting and charting soil-moisture and free-energy relations, and will doubtlessly continue to be useful.

In almost any soil-physics research or investigations of soil-plant-water relations, it appears essential that both quantitative soil moisture (mass of water per unit-mass of soil) and the forces with which moisture is held in the soil be determined and related. In studies relating to soil-compaction, and permeability, we are particularly interested in the free-energy of the soil-water at the higher moisture-contents (the macroporosity, as measured by the amount of moisture draining from the soil from pF 0 to about pF 2.5). In studies of rate of use and availability of water to plants, it is essential that free-energy moisture-percentage relations be established, and then there is the choice depending primarily upon direct measurements of moisture-content by routine sampling or of obtaining moisture-data from the free-energy data. Where circumstances permit, we prefer to obtain moisture-content data directly: (a) Because of the inherent variability of the soils with which we have worked, we feel the results we have obtained are more accurate despite the fact that each sample taken is of necessity from different soil; (b) soil-moisture free-energy relations appear to vary somewhat at moisture-contents approaching field-capacity during the life of some experiments; and (c) free-energy measurements are difficult to interpret where the soil is subject to appreciable temperature-variation.

L. A. RICHARDS (Bureau of Plant Industry, United States Department of Agriculture)--The following quotations are from the paper "Moisture retention by some irrigated soils as related to soil moisture tension", by L. A. RICHARDS and L. R. WEAVER, and appear to be related to the subject for discussion. The above paper is in the process of publication in the Journal of Agricultural Research.

"If pF is to be accepted as a free-energy scale it should be correctly used and should be clearly distinguished from pressure deficiency or soil-moisture tension. In leached soils, of course, the osmotic component of the pF can be negligible but in normal soils from semi-arid or irrigated regions dissolved material may account for the major part of the free-energy of the soil-water. For example, BOTELHO DA COSTA [see 1 of "References" at end of discussion] measured freezing-points for 14 California soils supplied by VEIHMEYER and found that the average pF at the moisture-equivalent was 3.07. DAY [2] using a different freezing-point technique on another set of 14 California soils found the average value of the pF at the moisture-equivalent to be 2.97. If osmotic effects are neglected, the calculation of tension-values from these pF-values given 1175 and 987 cm of water, whereas both theoretical and experimental results in a preceding section of this paper indicate that soil-moisture tension at a moisture-percentage equal to the moisture-equivalent will account for less than half of these energy values . . . . . .

"Tensiometer, suction-plate, pressure-plate, pressure-membrane, or centrifugation apparatus may be used for determining equivalent negative pressure on soil-moisture tension, but, without neglecting osmotic effects, cannot be used for determining pF if the latter is to be taken as a free-energy scale as originally proposed."

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[1] J. V. B. DA COSTA, The indirect determination of the "wilting coefficient" by the freezing-point method, and the influence of the salts upon the pF at that critical moisture content, J. Agric. Sci., v. 28, pp. 654-662, 1938.
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B. T. SHAW (Agricultural Research Administration, United States Department of Agriculture)--I do not believe there is any longer any argument regarding the desirability of describing the physical state of water in soil in terms of free-energy, soil-moisture tension, or pressure-potential rather than in terms of mass of water per unit-mass of soil. SCHOFIELD defined pF as the logarithm of the distance in cm above a free-water surface at which water would have a corresponding free-energy. Where osmotic effects can be neglected, it would be permissible to use pF as the logarithm of the soil-moisture tension expressed in cm of water; however, it would always be necessary to point out that osmotic effects are negligible. The pF is frequently used as the logarithm of the soil-moisture tension in systems where nothing is known about the osmotic effects. This has been particularly irritating to scientists who insist on rigorous discussions. Perhaps this consistent misuse of the term is sufficient reason for wanting to use other nomenclature. RICHARD'S terminology for soil-moisture tension seems to be simple enough for both written and oral discussion. It is easy to say "the 15-atmosphere percentage", "the third-atmosphere percentage", etc., by which are meant the soil-moisture contents corresponding to soil-moisture tensions of 15 atmospheres, 1/3 atmosphere, etc. It may take a little time to get used to these terms but they probably will not be misused as pF has been. Using semi-logarithmic paper as GARDNER suggests makes it possible to plot soil-moisture tension against moisture-content when soil-moisture tension is expressed either in cm of water or atmospheres.

L. K. SHERMAN (Consulting Engineer, Chicago, Illinois)--GARDNER has made reference to the supply-phase of soil-moisture. In a paper entitled "Infiltration and the physics of soil-moisture", presented at the Berkeley (California) meeting, Section of Hydrology, American Geophysical Union, in February, 1944, the writer noted the following:

(a) The supply of capillary moisture into the root-zone, (excepting the top layer of five to seven inches) is furnished by gravity water penetrating the soil through the non-capillary porosity or "channels".

(b) When gravity water has penetrated down the zone of soil completely filled with capillary moisture, and has filled all of the intervening capillary porosity, then there is no further capillary abstraction. The rate of infiltration and the rate of gravity flow through the soil proceeds at a uniform, minimum rate (assuming that the supply continues). This constant minimum rate of percolation is designated by the symbol f_c.

(c) Lateral capillary movement of water continues from the "channels" even though rain ceases, so long as there is any storage in the noncapillary porosity or until all capillary porosity has been satisfied.

(d) The ultimate constant rate f_c, in the same soil, is materially increased by vegetal cover or rather its root-systems. This is not due to any change in the percentage of non-capillary porosity. It may be due to the opening of constriction in the non-capillary porosity or, as GARDNER aptly puts it, "dependent upon the geometry of the void-spaces".

(e) The "net" mass-curve of infiltration, namely, $(f - f_c)$ is the same for all kinds of covers, on the same soil. This is BARNE'S hypothesis.

From all of the foregoing [(a) to (e)], it seems evident that the rates of infiltration are the sum of two rates of flow. One following the hydraulic laws of gravity flow, the other following the laws of the capillary movement of water.

There is nothing in this statement that conflicts with BAVER'S pF-relation as mentioned by GARDNER or with other equations expressing the rates of infiltration, such as those of HORTON [see 1 of "References" at end of discussion] or those of SHERMAN and MAYER [2]. All three are empirical or hybrids, although useful in practical applications. The writer, however, is of the opinion that better results, more in accord with all of the different phenomena of infiltration and moisture-supply, will be secured by recognition of the two separate phenomena.

In the simpler depletion-phase of soil-moisture dynamics, where capillary movement alone is concerned, pF may be a useful instrument. In the infiltration- or supply-phase a quantitative procedure which permits the sum of all computed parts to be checked against observed totals, is essential. This seems to preclude any use of pF.

References

[1] R. E. HORTON, Simplified method of determining an infiltration-capacity curve from an infiltrometer-experiment, Trans. Amer. Geophys. Union, Part II, pp. 570-574, 1942.
[2] L. K. SHERMAN and L. C. MAYER, Application of the infiltration-theory to engineering practice, Trans. Amer. Geophys. Union, Part III, pp. 666-677, 1941.

R. E. STEPHENSON (Oregon State College)--I have found the method of expressing the tightness with which water is held in the soil in terms of pF helpful in visualizing moisture-plant and moisture-soil relationships. I realize that the configuration of the void-space in the soil may vary greatly in different soils, and that this may influence the movement of moisture through the soil. Likewise, the removal of moisture from the soil by the plant is influenced by the configuration of void-space. That is perhaps shown by the wide range of moisture-content over which plants may be said to be wilting or experiencing shortage of moisture in some soils, compared to the narrow moisture-range for wilting in others. There seems to me to be a need for the expression of soil-moisture in both percentages and in terms of pF. I then have a better picture of plant-behavior in different soils and at different moisture-contents.

R. P. THOMAS (University of Maryland)--I believe the energy-method of studying water is very desirable. It probably is the most scientific approach which we have made. However, from the practical standpoint it has little value. This is because it cannot be determined as easily as pH. I do not think it can be compared with pH because of that difficulty. If it was a convenient method of measuring, I am sure it would soon become popular.

F. J. VEIHMEYER (University of California)--Probably no one will object to the interpretation of soil-moisture problems by means of energy-changes. The most helpful conception of soil-moisture phenomena, whether from consideration of its use by plants, the way it is held in the soil, or its movement, is gained by consideration of energy-relations. The energy necessary to remove water from soil can be measured. Whether this energy should be referred to as ergs per gram or as the logarithm of the height of a column of water which the water in the moist soil could support, when properly connected to a water-supply, is the pertinent question under discussion.

The use of the term pF because it has the sole advantage of reducing large numbers to small ones is debatable. Of course, it is easy to learn a new scale, but there may be danger in doing so when plotting soil-moisture contents against these scale-values. For example, it may be entirely fortuitous to pick out a point on the curve plotted so that the relation between the soil-moisture content and the logarithm of the heights of a column of water in equilibrium with the soil at the various moisture-contents, as is done when the pF-scale is used, and to place significance upon it because of the shape of the curve. If the curve showing the relation between moisture-potential and soil-moisture is a hyperbola, plotting with both coordinates as logarithms would give a straight line and there would be no point of inflection as might be the case when plotted with one coordinate scale as logarithm and the other as common numbers.

Measurements of soil-moisture usually are made for one or more of the following reasons, to find the amount of water in the soil, how much is available to plants, and how tightly the water is held by the soil. Using the pF-scale alone will not indicate the amount of water in the soil. It will not give the amount readily available to plants. It will, however, indicate whether the water is available or not if the correct value of the pF at the permanent wilting-percentage is known. It would seem much more logical to give the actual moisture-content together with the permanent wilting-percentage. Then the amount of water above this level or any other one taken as the base for reference is apparent from the data.

Since, as GARDNER points out, the logarithm of the potential does not enter the equation for flow, a conversion of the pF-values must be made to basic units before they can be used. This introduces an additional calculation. The justification for the use of the pF-scale seems to rest solely upon its convenience. It does not serve to explain soil-moisture phenomena any better nor does it make soil-water relationships clearer than where the data are plotted on an arithmetical scale.

C. M. WOODRUFF (University of Missouri)--The complexity of the soil-moisture system is attested by the numerous and varied approaches of investigators, and the numerous soil-moisture constants that have been advanced during the past few decades. Not until SCHOFIELD took this mass of uncorrelated information and converted it into a common denominator -- the pF-curve-- did the significance of the results of the earlier investigations become apparent. A knowledge of

the concepts of hydrodynamics and thermodynamics is not essential to a working knowledge of the soil-moisture system following the presentation of SCHOFIELD.

The pF-curve possesses more than a historical value. In a single, well-proportioned, and conveniently-sized curve it describes more fully and completely the soil as a physical entity than any other single criterion available. Moisture-contents between significant points on the curve, coupled with the shape of the curve, between these points, supplies information on soil-aeration, soil-permeability, soil-moisture, soil-texture, and soil-structure. SCHOFIELD pointed out numerous significant moisture-points along the curve. The full potentialities of the information contained in the shape of the pF-curve have not been realized, although some progress in this direction has been made. BAVER pointed out the relation of the flex-point of the curve to percolation. BRADFIELD and JAMISON presented curves for graded sands, and WOODRUFF presented curves on the effect of hydration of the soil-colloids as the soil-structure was destroyed by stirring.

Much is to be learned about the dynamics of soil-moisture movements and the physical state of the water in the soil. This knowledge may explain points of significance along the curve, such as the field-capacity and the wilting-point [Proc. Soil Sci. Soc. Amer., 1941]. However, these points, if established, are not premised on the concept of a pF. The pF-curve is only a convenient method presenting them with respect to other well-known soil-properties.

The future use of pF in soil-moisture literature will depend upon the extent to which it supplies a need for such a quantity. The introduction of the pH of chemistry met with considerable opposition from the older chemists, who were accustomed to the use of more cumbersome methods of expression. However, the use of pH has assumed a position without question today.

Closing comments by WILLARD GARDNER (Utah Experiment Station)--I find all the comments interesting. I repeat that the pF-concept has no doubt served a useful purpose and has found its way permanently into the literature of soil-physics. It seems to be implied in one or two instances, however, that the logarithm of the free-energy can be comprehended as a physical entity more readily than the free-energy itself, and with this I cannot agree. It would be possible, for example, to write the perfect gas law in the form

$$(pP + pV) = (pN + pR + pT)$$

the lower case p being used in the same sense as in the expressions for pH and pF, but I can find no means of obtaining these numbers without first having obtained numbers for P, V, N, R, and T, and it would be even more difficult to attach physical meaning to the equation without first attaching physical meaning to the entities, P, V, R, and T.

On the basis of the DARCY law, we might deduce the relation

$$pv = p(-k\nabla\Phi),$$

but it cannot be written in the form

$$pv = (-pk\ -\nabla p\Phi)$$

and this may serve to illustrate tremendous difficulties that would arise in the analytical procedures of theoretical physics in any effort to replace physical entities by their dimensionless logarithms.

I believe attention should be called to the fact that the free-energy of a substance does not necessarily represent the energy it contains. The free-energy of a gram of saturated water-vapor is the same as the free-energy of a gram of water at the same temperature, notwithstanding the fact that the heat of vaporization at 100°C is approximately 539 calories and that only about 7.5 per cent of this energy is used in the work of expansion. The actual increase in internal energy would be about 2.09×10^{10} ergs, or an amount sufficient to lift the gram of water approximately 132 miles against the field of gravity. Making use of RICHARDS' value of 16 atmospheres tension for the wilting-point, we may compute the energy required to remove a gram of water from a soil at the wilting-point and return it to a soil that is saturated, and this is found to be approximately 1.62×10^{7} ergs, or about one-twelve-hundred-ninetieth part of this computed internal energy-increase. Is it not, therefore, possible, that wilting may be due to the slow movement of the water into the plant from a dry soil and not to the excessive amount of energy required to remove it from the high-tension moisture?

It should be noted in particular that the free-energy increase, $\int dp/\rho$, for an incompressible fluid may be made indefinitely large by an increase in pressure, the work required, $\int pdv$, vanishing completely. Increasing the pressure does increase its free-energy but not the energy it contains.

REPORT OF COMMITTEE ON LAKES, 1943-44

S. T. Harding, Chairman

The organization of the Committee on Lakes was completed during the year with the following membership:

Thomas C. Adams	C. S. Howard	Ralf R. Woolley
Phil E. Church	Adolph F. Meyer	S. T. Harding, Chairman

Each member of the Committee has continued his own investigations in the field of lakes to such extent as war-conditions have permitted. No general Committee programs have been undertaken because of the same conditions. It is planned to maintain the organization of the Committee so that it may be available for work in its field when general investigational work can be resumed.

[See p. 808 for addendum by RALF R. WOOLLEY.]

12 Engineering Building,
Berkeley, California

REPORT OF COMMITTEE ON GROUND WATER, 1943-44

S. W. Lohman, Chairman

H. F. Blaney	C. S. Howard	H. T. Stearns
J. Harlan Bretz	G. W. Musgrave	V. T. Stringfield
Edward Burwell, Jr.	A. M. Piper	Max Suter
V. C. Fishel	N. A. Rose	C. V. Theis
Willard Gardner	A. N. Sayre	L. K. Wenzel

The Chairman extends an apology to G. W. MUSGRAVE for omission of his name from the list of members given in the report of the Committee on Ground Water for 1942-43.

The response from members of the Committee in general has been very gratifying and is much appreciated. Four new members, Messrs. H. F. BLANEY, EDWARD BURWELL, Jr., A. N. SAYRE, and V. T. STRINGFIELD have been added to the Committee this year, in order to effect better technical and geographic coverage.

The Sub-Committee on Permeability of the Committee on Ground Water has been active during the year under the chairmanship of L. K. WENZEL and now comprises the following thirteen members: B. A. BAKHMETEFF; V. C. FISHEL; L. P. HATCH; M. K. HUBBERT; O. W. ISRAELSON; C. E. JACOB; W. C. KRUMBEIN; W. B. LANGBEIN; O. E. MEINZER; MORRIS MUSKAT; L. A. RICHARDS; C. V. THEIS; and L. K. WENZEL (Chairman). Unfortunately WENZEL had to undergo a major operation at about the time of the annual meeting of 1944 and was unable to be present. During his illness W. B. LANGBEIN, as Acting Chairman, carried on the work of the Sub-Committee and has prepared a progress-report which is given in Appendix A.

The paper by A. M. PIPER on "A graphic procedure in the geochemical interpretation of water-analyses" and the discussions of this paper by R. A. HILL and W. F. LANGELIER [Trans. Amer. Geophys. Union, Part VI, pp. 914-928, 1944] constitutes a symposium on the interpretation of chemical analyses of ground water with respect to source and movement of the water and to changes in chemical character within an area. It is hoped that this paper and the discussions will stimulate the preparation of additional papers on the same general subject, particularly on applications of these methods to specific problems or areas.

O. E. MEINZER (United States Geological Survey, Washington, D. C.) has again submitted a timely statement regarding the work of the Geological Survey and cooperating State agencies on ground water for war purposes, which is given in Appendix B. He has also arranged for the preparation by Miss JEAN M. BERDAN, of the Geological Survey, of a list of current publications concerning ground water, which is given in Appendix H. In addition, MEINZER has written to me as follows regarding a number of activities that deserve special mention either because they are of research character or are otherwise of importance:

"As you know, there has been much activity and successful accomplishment in the application of discharging-well tests from which the coefficients of transmissibility and storage are computed. Four of the papers at the February 1944 meeting of the Society of Economic Geologists at New York were on that subject. I am impressed with several features of this work--one is the accuracy of results that are being obtained in some places where the formations are fairly regular and the conditions for the test are satisfactory; another is the many applications that can be made from the results of these tests. Probably an outstanding feature in the papers at the New York meeting was the geologic application that was made of the results of discharging-well tests. Thus the papers presented at that meeting were distinctly geologic papers but with effective use of the data obtained in the tests.

"There has been much interest in electric logging, and those who have used these results are generally enthusiastic over them. They have been available especially in Texas, Louisiana, and Mississippi. R. R. BENNETT has made considerable study of electric logging that he can apply to test-wells that are to be drilled in the Baltimore Area. As you know, electric logging has been used for oil-wells during the last 15 years or so, but the application to water-wells requires considerably different interpretation so that it forms a somewhat different subject. The Illinois Geological Survey is also making effective use of electric logging, and a paper on that subject was presented by C. A. BAYS and S. H. FOLK, of the Illinois Survey staff, at a conference of the Engineers Society of Western Pennsylvania in Pittsburgh. A discussion of that paper by N. A. ROSE was presented at the Pittsburgh meeting.

"The program that was started by C. E. CONDRA in Nebraska several years ago of systematic test-drilling in connection with our cooperative investigations has produced very good results both as to the geology and the hydrology of the areas covered. The plan of doing the test-drilling with well adapted State-owned rigs and geologist-drillers has proved especially effective. In Kansas you have operated successfully on the same plan for a few years, and the plan will doubtless be put into effect in other States. Your test-drilling facilities will afford an especially good opportunity for you to carry out your plan to investigate thoroughly the possibilities of the electric-resistivity method as an additional aid.

"V. T. STRINGFIELD has already written you of the deep-well exploration activities during the last year. The exploration of the drainage-wells in the limestone terrain in the vicinity of Orlando, Florida, was something new. The problem was largely as to the contamination of the limestone aquifer by draining sewage into it through wells. The current-meter showed the horizons at which the drainage-water goes into the formation and thus showed the sections through which contamination is occurring. This investigation was conducted by H. H. COOPER, Jr., and A. G. UNKLESBAY and was quite successful.

"Important investigations have been in progress involving the question of salt-water encroachment at Miami, Florida, and Long Beach, California. Both of these are elaborate investigations on which considerable money has been spent and on which quite definite results have been obtained. The paper at the New York meeting by BROWN and PARKER gave a part of the results of the Miami investigation, but a comprehensive and detailed report is nearing completion. There will also be released in the near future a good summary report, which will show rather definitely what Miami and other cities of southeastern Florida will have to do in order to preserve their fresh-water supplies. H. C. BARKSDALE, D. J. CEDERSTROM, and M. J. MUNDORFF, and in fact all of the men working on the Atlantic and Gulf Coastal Plain, have been dealing with problems of salt-water encroachment.

"In the several months which C. V. THEIS spent for the Army Engineers on ground-water developments along the Alaska Highway, he gave considerable study to the origin of permafrost and its engineering effects. He has found evidence that permafrost may be formed under present climatic conditions with certain conditions of surficial insulation, such as snow, surface-water bodies, frozen and wet soils, moss, etc.

"Another subject that is developing rather rapidly and has received much consideration during the past year is that of artificial recharge. As you know, there is now a large amount of recharge in Brooklyn by placing water that has been used for cooling into wells. An interesting experiment is also in progress on Long Island in which recharge is accomplished by putting water into a recharge-basin. In New Jersey recharge is accomplished chiefly by building reservoirs which impound water that goes through the sandy banks and bottoms of the reservoirs.

"For some time I have been calling attention, at every opportunity, to the greater use that could be made of some of the ground-water reservoirs by recharging them in the winter with cold water from a surface stream. We consider that it would not be good policy for the Government to consider recharging with any water that is not pure, but my idea is especially to use water from public waterworks during the winter season when the water is cold and the consumption is at a minimum, so that the facilities of the waterworks are not being fully utilized. It is my view that eventually special rates will be made for off-peak winter use, and that any city with a surface water supply that will be progressive enough to furnish water at cost during off-peak winter seasons will have a decided advantage in attracting industry. C. F. MERRIAM advocates the same policy in

Baltimore where the public waterworks obtain their supply from surface sources but where there is heavy industrial pumping from wells. He uses the interchange of electric current furnished by different hydroelectric and steam plants as an analogy for using water from wells for cooling in the summer, and using cold water from the city supply in the winter and also recharging with cold city water.

"Thus far it has been difficult to obtain any action along the line suggested in the foregoing paragraph, as water departments are cautious in regard to any suggestion for reduced rates and industries are loath to use high-priced water for recharging aquifers from which someone else may get the benefit. However, with the aid of the War Production Board, some progress along this line has now been made in Louisville, Kentucky. I have just received a letter from W. T. STUART, of our Louisville staff, in which he describes a test in which more than 33 million gallons of cold city water were run into a RANNEY collector in a period of 24 days. The rise in the water-level was observed in a number of observation-wells, and it approximated closely the rise that had been computed from calculations based on specific yield and coefficient of transmissibility.

"There are in the aggregate a considerable number of artificial recharge projects. They are in different parts of the country and they differ greatly in character. Some of them are producing successful results, and it appears that extensive use of the ground-water reservoirs by means of artificial recharge is a subject of considerable importance and that eventually there will be a large amount of artificial recharge in places where it is practicable and where the water is of sufficient value to make it economically attractive. I have thought of requesting each one of our field offices in States in which there is any artificial recharge-project, to prepare a paper describing these projects. This would be somewhat comparable to our salt-water symposium three years ago. The principal reason why I hesitate to do this is because it would inevitably impose another burden on our men who are already heavily loaded with work. Another suggestion would be to have a symposium on the subject sponsored by your Committee a year hence. Indeed, we might carry out both plans and use some of the Survey papers in a symposium by the American Geophysical Union. I would be glad to get your opinion on this question."

MEINZER has suggested a symposium on the timely subject of artifical recharge to be sponsored by the Committee on Ground Water. It is my understanding, however, that such a symposium is being arranged by V. T. STRINGFIELD for presentation at the annual meeting of the Society of Economic Geologists at New York in February, 1945.

Attention is called to an interesting symposium on "Limiting factors of perennial yield of artesian reservoirs" arranged by V. T. STRINGFIELD, of the Geological Survey, and presented at the joint meeting of the Society of Economic Geologists and American Institute of Mining and Metallurgical Engineers at New York on February 23, 1944. Abstracts of the five papers comprising this symposium were published in the January-February 1944 issue of Economic Geology, and the full papers are to appear in later issues of the same journal. The following papers were presented by the authors named--all of whom are members of the Geological Survey: (1) Problems of the perennial yield of artesian aquifers, by O. E. MEINZER; (2) The perennial yield of artesian water in the coastal area of Georgia and northeastern Florida, by M. A. WARREN and H. H. COOPER, Jr.; (3) Geologic factors affecting the perennial yield of artesian aquifers in three areas in Mississippi, by G. F. BROWN; (4) Quantitative studies of some artesian aquifers in Texas, by W. F. GUYTON and N. A. ROSE; and (5) Salt-water encroachment in limestone at Silver Bluff, Miami, Florida, by R. H. BROWN and G. G. PARKER.

H. F. BLANEY (Soil Conservation Service, Los Angeles, California) has submitted an interesting report on ground-water investigations in the Southwest, which forms Appendix C to this report.

EDWARD B. BURWELL, Jr. (Office of the Chief of Engineers, Washington, D. C.) has submitted a brief account of ground-water investigations made during 1943 by the Corps of Engineers, United States Army, which forms Appendix D to this report.

V. C. FISHEL (United States Geological Survey, Lawrence, Kansas) has prepared a brief description of pumping tests conducted at Kansas City, Kansas, by the Corps of Engineers, United States Army, which forms Appendix E to this report. FISHEL was invited to participate in these pumping tests. A detailed report of these tests ultimately will be published by the Army Engineers.

G. W. MUSGRAVE (Soil Conservation Service, Washington, D. C.) has submitted the following statement, including very pertinent remarks about the need for more exact data on the relationship of infiltration to ground-water supplies (see also statement by MAX SUTER).

"The Illinois State Water Survey has the study of the problem of the ground water in the Peoria Area well under investigation, as indicated by SUTER'S paper presented at the meeting last spring. We are merely minor cooperators in a broad investigation and our attention has been confined to

studies of infiltration at the surface above the supposed location of the aquifer.

"I believe it is obvious to all of us that information in regard to the relation between infiltration and ground water is extremely meager. Yet it may be of the utmost importance. Hence my suggestion would be that as far as may be possible the Committee should encourage investigations wherever feasible into these possible relationships. So far as I am aware we have very little information which would indicate the amount of infiltrated water necessary to meet the draft upon ground water in various parts of the country, whether or not there is an excessive time-lag between the occurrence of infiltration and the appearance of an increment of it in ground water, and the many diverse conditions which obviously have a bearing upon the whole matter. As well pointed out by MEINZER in "Hydrology", the present-day concept recognizes infiltration as a source of much of the ground water, yet I believe the facts of the matter are that we know comparatively little about many of these problems at the present time. If our Committee on Infiltration can work along with your Committee on Ground Water, we shall be happy to do so and I would hope that some progress might be the result."

N. A. ROSE (United States Geological Survey, Houston, Texas) reports as follows concerning current hydrologic research by the petroleum industry:

"I have talked with several of the oil geologists in the last few weeks in an attempt to learn of any new research that is being carried on by the oil companies. According to these men there is nothing of importance to add to the report of 1943. Most of the activities included in that report are still being carried on, however most of the research now being done by the oil companies is directly associated with the war effort.

"An interesting procedure by the Quintana Petroleum Company in the Washburn and Green Branch Oil Fields in south Texas was related by R. W. SUNDSTROM, United States Geological Survey, Austin, Texas. When a well is found to be 'dry' or unproductive it is generally converted into a water-well by perforating the casing opposite the Carrizo sand, of Eocene age. The depths of the perforations range from about 3,000 to 5,000 feet. All of the wells flow, the maximum flow being about 500 gallons per minute. The temperature of the water is more than 100°F. A temperature of 150°F. was recorded in a well about 5,000 feet deep. The water is of good quality and is used for irrigation and stock. The water from a few of the wells is used to heat some of the ranch houses by circulation through a series of pipes."

A. N. SAYRE (United States Geological Survey, Washington, D. C.) has submitted an interesting statement of ground-water studies conducted in Central America by members of the Geological Survey for the Coordinator of Inter-American Affairs, which forms Appendix F to this report.

H. T. STEARNS (United States Geological Survey, Honolulu) reports as follows:

"During the past year I have been engaged in ground-water investigations in the Hawaiian Islands, various islands in the southwest Pacific, and Ascension Island in the Atlantic Ocean.

"G. A. MACDONALD, of the United States Geological Survey, has continued ground-water studies in Hawaii. W. O. CLARK has continued his Hawaiian ground-water studies as geologist for the Hawaiian Sugar Planters' Association. C. K. WENTWORTH, Geologist for the Honolulu Board of Water Supply, has continued ground-water investigations in the Honolulu Area, and has carried on laboratory experiments dealing with the flow of liquids through very small apertures."

V. T. STRINGFIELD (United States Geological Survey, Washington, D. C.) reports as follows concerning cooperative ground-water studies in the southern States and on current research on the hydrology of limestone terranes:

"In connection with ground-water investigations in Florida by H. H. COOPER, Jr. and A. G. UNKLESBAY of this Survey, in cooperation with the Florida Geological Survey and the United States Engineer Office, a deep-well current-meter was used in investigating drainage-wells at Orlando, Florida, to determine the depth at which contaminated surface water draining into the wells entered the cavernous limestone penetrated by the wells. The deep-well current-meter, of course, has been used to detect leakage of water from one formation to another through a well. However, this probably is the first use of the meter to indicate the depth at which surface water enters a water-bearing formation through a well.

"Ground-water investigations by W. F. GUYTON and others in cooperation with the State Geologist of Kentucky and the City of Louisville are in progress in Louisville to determine the safe yield of the water-bearing formations in that area. Large quantities of ground water are required in that area for use in making industrial alcohol and for war plants. Most of the ground-water supply is obtained from shallow sand and gravel which are underlain by limestone and shale. A relatively small part of the water is obtained from the limestone. In investigating the safe yield of the aquifers, studies are being made to determine the recharge from the Ohio River to the shallow sands and gravels, and tests are being made to determine the feasibility of recharge-wells and recharge-basins.

"In your letter of February 25, you inquire about current research on the hydrology of limestone terranes. . . . .The paper by WARREN and COOPER, which constituted part of the symposium at the New York meeting of the Society of Economic Geologists deals with quantitative studies of artesian water in limestone. . . . . .The investigations at Louisville, as has been indicated, include a study of the limestone underlying that area. The investigation at Orlando, Florida, deals with cavernous limestone. Such investigations as those in the cavernous limestone of Florida will eventually indicate the relation of the vertical distribution of the caverns to the lower stages of sea-level during Pleistocene time. With reference to occurrences of cavities in limestone at considerable depth below sea-level, it may be noted that in a paper 'Developments in southeastern United States in 1943' by URBAN B. HUGHES [pp. 74-75, Digest of meeting Amer. Asso. Petrol. Geol. at Dallas, Texas, March 21-23, 1944], cavernous limestone is reported to have been penetrated at a depth of 11,613 to 11,626 feet in a well in Sec. 30, T. 48 S., R. 30 E., near Sunniland, Collier County, in southern Florida.

"Electric logs are being used to good advantage in Louisiana, Mississippi, and Texas. MAHER, JONES, BROWN, ROSE, and others have given considerable attention to the interpretation and the use of electric logs on ground-water studies. A study and interpretation of electric logs, together with research to determine the most suitable type of equipment for use on water-wells, is worthy of special research. MAHER and BENNETT are giving some attention to the possibility of having equipment available for use in any part of the country [see statement by R. R. BENNETT].

"The United States Engineers office has made some use of wells to control sand boils along the levees of the lower Mississippi River. . . . .

"With reference to recharge from surface streams, it can be added that in one of the military areas of the Coastal Plain of North Carolina, but near the Fall Line where the more productive sedimentary formations are thin or absent, studies were made by M. J. MUNDORFF, of the Geological Survey, in cooperation with the North Carolina Division of Geology, to determine recharge from a surface stream to the shallow water-bearing sand."

MAX SUTER (Illinois State Water Survey Division, Urbana, Illinois) writes as follows concerning continuing ground-water studies in Illinois (see also statements by G. W. MUSGRAVE and Appendix G by M. M. LEIGHTON):

"As Engineer of the State Water Survey, I am in charge of the ground-water studies in the Peoria-Pekin Area, East St. Louis Area, and in the Chicago-Joliet Area. These investigations are made along the lines described in my paper before the 1943 meeting of the American Geophysical Union and in the Illinois Engineer of February 1942, and the Journal of the American Water Works Association [vol. 35, p. 921, 1943]. Much more material has been accumulated, especially on the influence of the floods of June, 1943, on ground water. Refinements including studies of sand-boils, application of the THEIS method of calculation to some special problems, mapping of infiltration-areas relative to infiltration-capacities, and more quantitative studies of infiltration are planned. Studies are also under way on the permeability of graded materials. Mathematical studies are under way for the application of the THEIS method to variable flow. Special preliminary investigations were also made for an inventory of wells and determination of pumpage and recession of the ground-water level at Rockford and in the Rock Island-Moline Area. So far none of the results has been published.

"The State Water Survey also makes routine chemical analyses of ground water from all over the State of Illinois, conducts well-production tests, collects data on wells and gives information on the best chances for well-locations, in cooperation with the State Geological Survey. In 1943 it published Bulletin 35 on Ground-water supplies of the Chicago-Joliet-Chicago Heights Area.

"The State Geological Survey has in preparation a map of the pre-glacial valleys in Illinois, which will be of great help in locating favorable well-locations in the glacial drift. The State Geological Survey also is making many earth-resistivity surveys for the location of water-bearing strata in alluvial and glacial deposits, and also electrical logging of water-wells as described in the Journal of the American Water Works Association [vol. 35, pp. 911-920, July, 1943].

"We have one problem that resists explanation. We find that ground-water levels in drift-wells vary with the river-stages and that the ground water goes down even when its level is below the river-stages, in many cases the ground-water level being constantly 10 to 20 feet below the river-level. The question is, where does the water go when it has no head for an outlet? We would like to learn of similar experiences in other localities.

"The longer we study a problem, the more we find that conceptions accepted as evident or obvious are in reality not quite accurate or general. It is generally difficult to displace such wrong conceptions, but the Committee should collect some typical cases and endeavor to correct such inaccurate assumptions.

"An exchange of publications of local character should be arranged between the members. (Although I have not yet read all the publications you sent me, I have found some valuable suggestions.)"

L. K. WENZEL (United States Geological Survey, Washington, D. C.) reports as follows (see also statements by O. E. MEINZER and V. T. STRINGFIELD and Appendix A by W. B. LANGBEIN):

"I have not been actively engaged in research during the last year. Attention might be called, however, to the paper by GREENLEE and myself published in the Transactions for 1943 [pp. 547-564], since this method of determining transmissibility and storage-coefficients is the most general method yet devised and has been used during the year in several localities. Attention might be called also to the fact that KAZMANN and I worked out a formula for computing the quantity of water that will be taken from storage during any interval of pumping and in any area around the pumped well. By the use of this formula the amount of water that is assumed by the non-equilibrium formula to percolate from beyond any specified distance in any given time can be computed and thus the effects of boundaries on forecasting declines in water-level can be evaluated to some extent. This formula has not been published as yet.

"Pumping tests to determine transmissibility- and storage-coefficients have been used on an increased scale during the last year to aid in determining the well-water supplies at military establishments and for war industries. It is believed that much of our success in developing and maintaining the well-water supplies for war activities has been the result of the use of the pumping-test methods. The work of KAZMANN, SCHAEFER, and JEFFORDS in developing methods for determining the productivity of well-water supplies, whose chief source is a nearby stream, is particularly noteworthy. KAZMANN pioneered this work at the Indiana Ordnance Works, Charleston Indiana, where 50 to 60 million gallons of water are pumped daily from wells situated within a few hundred feet of the Ohio River. The effects of changes in the temperature of the water throughout the year makes problems of this kind very difficult to solve. JEFFORDS has recently made a good study of the Parkersburg, West Virginia, supply which is obtained from a line of wells along the bank of the Ohio River. Data are available on changes in water-temperature, river and ground-water levels, and on changes in various constituents of the well- and river-water. BRASHEARS is engaged on some recharge-experiments at the Grumman Aircraft Plant on Long Island which should probably be mentioned in your report. An important experiment is being carried on at Louisville to recharge the underground formation in the vicinity of several distilleries with city water during the winter months in order that sufficient water of low temperature will be available during the summer months to provide an adequate supply for the distilleries. CEDERSTROM has information on a similar experiment that has been carried on for some years near Hopewell, Virginia, for a war-plant.

"It would seem fitting that a statement in your report should relate to the work of the ground-water hydrologists that have been assigned to special water-supply duty in the armed forces. It is my understanding that these men have accomplished a great deal although no specific information on their work is available [see Appendix B, by O. E. MEINZER]. Doubtless their efforts will be felt more as the war progresses. I might suggest that a symposium be arranged on the artificial recharge of underground formations and believe contributions might be solicited from a great number of men, including BRASHEARS, GUYTON, SUTER, PIPER, and CEDERSTROM [see statement by O. E. MEINZER].

"Let me suggest that consideration be given for the Committee report of 1945 and other reports to the idea of requesting each member of the Committee to prepare a paragraph or two on any detailed phase of ground-water hydrology that he considers a contribution and which is unpublished at the time. This part of the Committee's report could easily become extremely valuable in several ways. If the Committee member's name were given together with a short title, such a paragraph or paragraphs would constitute the first place of reference for important contributions. In addition, it would provide current publication of ideas and contributions that otherwise might not be made available for several years. The success of such a procedure would probably depend to a large degree on the method in which the paragraphs were set apart from each other to make them as small separate articles."

The Chairman is greatly interested in this suggestion by WENZEL regarding the preparation of future statements for the Committee reports, and will welcome additional suggestions along this line. The appendices to the present report serve this purpose in part.

M. M. LEIGHTON (Chief, Illinois Geological Survey, Urbana) has submitted a very comprehensive report on the ground-water studies being carried on by the Illinois State Geological Survey by geophysical and other methods, which forms Appendix G to this report (see also statements by MAX SUTER).

H. C. BARKSDALE (United States Geological Survey, Trenton, New Jersey) states as follows:

"Research in this office has necessarily been cramped by a shortage of personnel and an overabundance of work. We are, however, retaining our interest in obtaining whatever information we can upon problems relating to salt-water intrusion and artificial recharge of water-bearing sands.

In both of these fields I think some material is developing that may someday be worth while if we can only get a chance to collect it now and evaluate it later."

R. R. BENNETT (United States Geological Survey, Baltimore, Maryland) makes the following statement regarding current ground-water work in the Baltimore Area in cooperation with the State Geologist of Maryland:

"Inasmuch as our time is spent largely on the investigation of the ground-water resources of the Baltimore Area or miscellaneous field investigations in Maryland, little time is left to work on academic research problems. However, in connection with the study of the Baltimore Area, we have found it necessary to apply a variety of techniques in the exploration of wells for salt-water leaks. A recording milliammeter has been ordered. This instrument will be used with the electrode-outfit to obtain a continuous record of the relative conductivity of the water as the electrode is lowered in the well. We also are now constructing an instrument for the determination of the diameter of wells."

M. L. BRASHEARS, Jr. (United States Geological Survey, Jamaica, New York) writes as follows concerning current ground-water work on Long Island in cooperation with State and County agencies:

"The correlation of water-levels and precipitation on Long Island, New York, reported in page 415 of the Transactions of 1943, has been continued. Part II of the paper on that subject, entitled 'Correlation of ground-water levels and precipitation on Long Island, New York, Part II--Correlation of data' by C. E. JACOB, is published in these Transactions [pp.928-939]. The correlation-procedure which has been developed is an outgrowth of studies begun by Major R. M. LEGGETTE. This procedure, involving use of the cumulative departure of precipitation from a progressive or running average, is valid for long-term trends of water-levels. In order further to study short-term trends of water-levels a north-south line of shallow recorder-wells has been established in the central part of Long Island. It is hoped that a continuing study of the records of these wells will throw much light on the effect of storm-intensity, condition of soil, etc., upon recharge to the water-table.

"Ground-water conditions in Brooklyn, New York, one of the areas designated as critical by the War Production Board, are of more than passing interest. The safe yield of the area has been exceeded for many years. As a result the water-table has dropped below sea-level and the water-bearing beds have been invaded deeply by sea-water at several places. The drilling of wells has been regulated stringently by the State since 1934 and some favorable results of the program of conservation are beginning to appear. Although the water-table in the center of the overpumped area is still approximately 27 feet below sea-level, it has risen progressively about two feet since late in 1941. Meanwhile, the inflow of sea-water has continued.

"Our work at some of the large war plants in the central part of Long Island has afforded the opportunity to obtain much operational information pertaining to methods of recharging. When time permits, we plan to release hydrologic data showing the rise and fall of the water-table resulting from recharge-activities and other related phenomena."

JACK B. GRAHAM (United States Geological Survey, Philadelphia, Pennsylvania) writes as follows concerning the reestablishment of ground-water work in Pennsylvania in cooperation with the Pennsylvania Topographic and Geologic Survey:

"This office was established in September of 1943, and work was started in the Philadelphia Region because of the importance of ground water to many industries situated in the area of ground-water production in south Philadelphia.

"To date my work has been centered largely at the Philadelphia Navy Yard, where the problem at the moment is to determine the source, movement, and corrective measures for iron-bearing waters which are appearing in the aquifer yielding water to the Navy well-field. This problem is being studied by the use of pumping tests, water-sampling, and geologic profiles.

"The observation-well program for the State is being continued, and new observation-wells have been established in the Philadelphia Region."

W. F. GUYTON (United States Geological Survey, Louisville, Kentucky) makes the following observations concerning pumping tests in the South conducted prior to his transfer from Texas to Kentucky:

"During the past year I had the opportunity of noting the check between actual drawdowns of water-levels in several artesian formations and drawdowns computed with the non-equilibrium formula. For the Carrizo formation at Lufkin, Texas, the average error in the computations was less than ten per cent for a period of three years, with total drawdowns of about 200 feet. The data are insufficient to permit a closer check. For the Travis Peak formation at Camp Hood, Texas, near Belton, the average error in the computations was three per cent for a period of 11 months, with total drawdowns of about 300 feet. For the Wilcox formation at Camp Swift, Texas, near

Bastrop, the average error in the computations was about ten per cent after equilibrium was reached in three months with total drawdowns of as much as 80 feet. A fault found by the original pumping tests was accounted for in the computations by the image-well theory, and it is probable that the fault is not continuous through the area as necessarily assumed. For three sands of the Fleming and Catahoula formations at Camp Polk, Louisiana, near Leesville, the average errors were four, seven, and five per cent for periods ranging from two months to two years, with total drawdowns ranging from 25 to 110 feet. These close checks give me considerably more confidence in the non-equilibrium formula."

R. M. JEFFORDS (United States Geological Survey, Morgantown, West Virginia) makes the following statement regarding cooperative ground-water investigations in West Virginia in cooperation with the State Geologist:

"In West Virginia the major part of the ground-water investigations during the past year have pertained to water-supplies of certain municipalities and large industrial plants whose water requirements have increased importantly because of expanding production for war. Most of the studies have been along the Ohio and Kanawha River valleys but specific local investigations were made in several other parts of the State.

"Detailed reconnaissance of wells obtaining water from the alluvium along the Ohio Valley indicates that many well-systems, even those producing as little as 250,000 gallons a day, receive a significant part of their recharge by infiltration from the adjacent river. The geologic data are too inadequate in most areas and water-level fluctuations are too misleading to permit easy decision as to sources of water. However, daily records of the well-water at Parkersburg for a 15-year period suggest that the fluctuations in hardness, temperature, and alkalinity (or bicarbonate) are significant, fluctuations in free carbon dioxide doubtful, and fluctuations in iron and pH of little or no value in interpretation of the source of the water. Although the concentration and constituents of the well-water may differ appreciably from those in the river-water, the correlation of fluctuations in the character of the well-water with changes in character and stage of the river furnish an indication of relationships.

"The graphic or diagrammatic representation of single analyses of water from many scattered wells along the Ohio Valley permits rapid tentative identification of well-waters composed of mixtures of river-water and normal ground water."

R. G. KAZMANN (United States Geological Survey, Memphis, Tennessee) writes as follows in regard to a current research problem:

"In the past year my principal research problem has been the relationship between rivers and adjacent aquifers. The problem from a water-supply standpoint may be stated as follows: If a river flows next to a permeable aquifer will the river-water replenish the aquifer if wells lower the ground-water table or piezometric surface? The river may recharge the aquifer in certain places and may not recharge it at others. Tests can be made to determine the relationship at any given location.

"If the river does recharge the aquifer, one of the most critical factors is the temperature of the river-water. Under the same conditions of gradient, the same aquifer will furnish about 50 per cent more water at 75°F than it will at 40°F. An extensive series of experiments is now being conducted to determine accurately the temperature-distributions existing in such an aquifer."

E. J. SCHAEFER (United States Geological Survey, Columbus, Ohio), recently transferred to Ohio, writes as follows regarding his work in cooperation with the Ohio Engineering Experiment Station:

"My work in Ohio at the present time consists in keeping in close touch with developments in the Mill Creek Valley near Cincinnati where numerous war-industries are dependent on water-supplies from ground-water sources and in establishing an observation-well program in the areas of heavy pumping in other parts of Ohio. In addition I am gathering geologic and chemical data whenever time permits."

G. C. TAYLOR, Jr. (United States Geological Survey, Baton Rouge, Louisiana), recently transferred to Baton Rouge, writes as follows concerning current ground-water work in Louisiana, largely in cooperation with the State Geologist:

"Ground-water investigations in Louisiana during 1943 included quantitative studies of problems of public water-supply in the Camp Polk Area, and at the cities of Alexandria and Natchitoches, of large industrial pumpage in the Lake Charles and Baton Rouge areas, and of pumpage for rice irrigation in southwestern Louisiana.

"At Camp Polk extensive pumping-tests were conducted to determine the perennial yield of aquifers in that area. These data together with information obtained from earlier test-drilling, sampling, electrologging, and chemical analyses present a composite picture of ground-water con-

ditions in that area and are described in restricted reports to the War Department by J. C. MAHER, W. F. GUYTON, W. J. DRESCHER, and P. H. JONES.

"At Alexandria a program of ground-water exploration by test-drilling was completed under the direction of J. C. MAHER and P. H. JONES. The program resulted in the development of a new well-field to supplement and ultimately to supplant an older, overdeveloped well-field in the city.

"At Natchitoches a similar test-drilling program, which included sampling of water-bearing sands, electrologging, and chemical analyses, was begun under the direction of J. C. MAHER and P. H. JONES. This program will indicate the proper location of new well-fields to supplant the present failing supply.

"At Baton Rouge observation of current ground-water conditions including water-level records and additional pumping developments were continued under the direction of P. H. JONES.

"An areal investigation of ground-water conditions in the Lake Charles industrial area and the contiguous rice-irrigation area in southwest Louisiana was begun during the year by W. J. DRESCHER and L. W. YOUNGQUIST."

S. F. TURNER (United States Geological Survey, Tucson, Arizona) reports as follows concerning current ground-water studies in Arizona:

"A large project has been in operation in the upper Gila Drainage-Area near Safford, Arizona, to determine transpiration by water-loving plants and evaporation from the soils typical of that area. Plants under intensive investigation are salt-cedar or tamarisk, baccharis, and cottonwoods. A large experiment station was installed and was in operation the larger part of last summer and during the following winter. This is the project that was discussed in our report to you dated April 3, 1943. The project is still in operation although it may be shut down at any time. We have released no data or information on the results as yet but we are obtaining a large number of valuable data regarding transpiration and evaporation, using not only the tanks described in our previous memorandum but also a large number of transpiration-wells equipped with recorders.

"One of the major problems in connection with the investigation described above is that of the specific yield of water-bearing materials. I have always felt that the problem of obtaining specific yield in a satisfactory, practical manner has not been solved. We are doing much work on this in connection with the above project and are obtaining valuable results but I cannot say that the problem of a satisfactory method is solved. We are determining specific yield by raising or lowering the water-levels in the large experiment-station tanks, by various laboratory tests, and by what we call miniature pumping-tests. By that I mean tests where the amount of water pumped is rather small and the observation-wells are from six inches to ten feet away from the pumped well. We hope to have something very worthwhile from the above work before we are through.

"We have used geophysics to assist in exploration for ground-water supplies for several big army camps in the desert. We have obtained valuable information on the use of geophysics which we hope to release after the war. Our principal conclusion regarding the resistivity-method is that it is very valuable when you can start with a probe by a well on which you have a detailed driller's log and a geologist's description of the samples. The work can then be extended to unknown areas but the interpretation must be made by a ground-water geologist working in cooperation with a geophysicist. We have not been able to locate ground-water level by resistivity but can locate beds that could bear water if they are below the water-table. The method is excellent for locating bed-rock under valley-fill."

H. A. WAITE (United States Geological Survey, Lincoln, Nebraska) reports as follows concerning current ground-water investigations in Nebraska:

"Investigations of the ground-water resources in Nebraska are being continued by the Federal Geological Survey in cooperation with the Conservation and Survey Division of the University of Nebraska. Systematic test-drilling programs were conducted in 1943 in the valleys of the Elkhorn and the North Loup Rivers using two State-owned portable hydraulic rotary drilling rigs. The Nebraska Bureau of Irrigation, Water Power, and Drainage, of the Department of Roads and Irrigation participated in the test-drilling activities. The character and thickness of the saturated water-bearing material in each of these valleys were determined and information was obtained on the configuration of the underlying bed-rock surface. Approximately 40 samples of water were collected for chemical analysis in order to study the chemical quality of the ground water in each valley.

"A report is now in preparation covering the results of a comprehensive test-drilling program that was conducted in the Republican Valley and its principal tributary valleys during 1939-42. Maps have been prepared showing the locations of approximately 825 test-holes drilled in connection with that program, and the thickness of saturated water-bearing material has been shown by means of isopachs constructed on the basis of test-hole information. The configuration of the underlying bed-rock surface has been shown by means of contours on the top of the bed-rock.

"Much of the investigational work in Nebraska has been liberally supplemented by test-drilling. Through this medium it has been possible to trace the sinuous courses of ancient alluvium-filled

channels and valleys in areas where there is no visible evidence at the surface of their occurrence. As a result, earlier concepts of the drainage-pattern of some of the principal ancestral stream-courses in Nebraska are being continually challenged. The delineation of some of these ancestral valleys is of great practical value in connection with the study of the ground-water resources of Nebraska.

"It has been found that the continuity, extent, facial changes, correlation, and relative position of various aquifers can be definitely established through an intelligent test-drilling program much more satisfactorily than can be done on a theoretical basis through a study of outcrop-areas. Much progress has been made to date toward a more complete and exact understanding of the relationships of the Pleistocene deposits of the glaciated part of the State to those of the non-glaciated part."

In Kansas several areal ground-water studies begun last year are being concluded, and new areal investigations are being started in the following areas: Pawnee County, by T. G. McLAUGHLIN; Barton County, by B. F. LATTA; and Norton County, by J. C. FRYE. The usefulness of electrical-resistivity methods as a supplement to test-drilling in determining depth to bed-rock in filled valleys is now being investigated thoroughly by V. C. FISHEL. The preliminary set-ups will be made at points where carefully logged test-holes have been drilled and which will serve as yardsticks for the evaluation of the geophysical results. The studies will be carried on first in the Kansas River Valley at Lawrence and later in the present and ancestral Republican River valleys in Republic County.

U. S. Geological Survey,
Lawrence, Kansas

APPENDIX A--PROGRESS REPORT OF THE SUBCOMMITTEE ON PERMEABILITY

W. B. Langbein, Acting Chairman

A variety of units and names of units relating to permeability have been used and are being used by different investigators. This Sub-Committee was recently organized to provide an open forum for persons of different background and experience to present their views in an orderly manner. Thirteen members representing diverse fields of activity have been chosen. To these, L. K. WENZEL, Chairman, by memorandum dated December 2, 1943, proposed three questions for consideration as an initial effort of the Sub-Committee: (1) Should the coefficient of permeability depend only on the structure of the material, or should some other name be used to express this property in view of the fact that, as now generally used, the coefficient of permeability is not independent of properties of the fluid or the combined properties of the fluid and the material; (2) should a name be coined, or is there a suitable one in existence, for expressing the combined properties of the material and fluid for practical application in one local area; (3) what are the parameters that should be included in the equation of flow of fluids that relate only to the structure of the material.

WENZEL also requested that field- and laboratory-viewpoints be kept in mind in considering these questions. Ten replies have been received--each has been rather complete. There is little uniformity of opinion, rather a stimulating diversity of viewpoints reveals an active interest in this subject. A folio of replies has been circulated among the members for their study and further discussion.

Most of the replies seem to favor reserving the term "permeability" to apply to the properties of the medium exclusively and free it from dependence on any property of the fluid. There is no unanimity as to whether viscosity is to be explicit or implicit, what expression is to be used, and its definition, or the kind of units to be employed. The spread is great, from a simple ratio, discharge per unit-area per unit-gradient, to a complex expression in which additional factors for gravity, density, and viscosity are expressed.

The following is a generalized expression for the laminar flow of water through a porous medium:

$$Q = [A1][g][\rho/\mu][\delta^2][f\alpha][f\ (\text{structure}) \ldots .]$$

The factors on the right are listed in decreasing order of our knowledge of their action. The first three, representing the studies of such men as POISEUILLE, HAGEN, and DARCY, are fairly well established, but comparatively little is known of the fourth and fifth and practically nothing of the sixth or succeeding factors.

In part the question before the Committee resolves into determination of which of the factors listed above shall be grouped under the term "permeability". Several terms have been proposed (including some newly devised ones) to represent various groups of factors. It would be a desirable goal (and hopefully not too ambitious) perhaps to narrow down the terms in use to an essential minimum and to assign to them precise meanings understood by all.

It does not seem expedient at this time to report in detail on the diverse and informative ideas (many of which are yet in a formulative state) expressed by the several Committee members, but we hope that a more detailed progress report can be made for the meeting in 1945.

U. S. Geological Survey,
Washington, D. C.

APPENDIX B--THE WORK OF THE UNITED STATES GEOLOGICAL SURVEY AND COOPERATING AGENCIES ON GROUND WATER FOR WAR PURPOSES

O. E. Meinzer

A report by O. E. MEINZER, published as Appendix B of the annual report of the Committee for 1942-43 [Trans. Amer. Geophys. Union, Part II, pp. 418-420, 1943], describes in some detail the previous work of the United States Geological Survey and cooperating agencies on ground water for war purposes.

The geologists from the staff of the Geological Survey listed in that report and several other ground-water geologists have served in the Army during the past year on water-supply assignments. Only sketchy and unofficial information is as yet available concerning the activities of these geologists, but it is believed that they are now all engaged in overseas theaters of warfare and that their services in water-supply and other technical work are of substantial value. In this service they have been supported by ground-water maps and reports furnished by the Geological Survey for the different theaters.

During the past year the work of the Geological Survey on ground-water supplies for war-purposes in this country was continued on a scale as large as in the previous year. This is somewhat surprising, as the major period of war-plant construction is past. However, numerous small plants and a few large plants are still being constructed and the production of others is being increased. The development of water-supplies for these new plants and follow-up work on existing industrial and war-affected public water-supplies has called for a large amount of continuing work. Also, construction of military and naval establishments has continued, and the water-supplies of existing establishments have required continuing observation.

During the past year the Water Resources Branch of the Geological Survey has made about 950 special reports on ground-water supplies for war purposes, including reports on both the United States and foreign countries, bringing the total to date to about 2,750. The principal agencies to whom the reports have been made are the War and Navy Departments and the War Production Board, but reports have also been made to numerous other Federal agencies and to industrial officials and consultants.

One of the ground-water geologists of the Geological Survey has visited most of the Naval bases in the Pacific and has rendered much practical help in regard to their water-supplies. This work related chiefly to volcanic terranes and to atolls. Similar work has been done for the Army, both in the Pacific and in the Atlantic.

At the request of the Office of the Coordinator of Inter-American Affairs, field investigations were made in El Salvador and other Central American countries, by two of the Survey's ground-water geologists, in part to develop water-supplies along the Pan-American Highway.

During the year members of the Geological Survey assisted in the preparation of the following technical manuals of the War and Navy Departments on ground-water supplies and well-drilling, especially for the use of water-supply companies and battalions: War Department Technical Manual 5-296, "Ground-water supply for military operations," 1944; War Department Technical Manual 5-297, "Well drilling," 1943; "Handbook on ground-water supplies," Bureau of Yards and Docks, Navy Department, 1943.

At the request of the Army, one of the Survey's ground-water geologists was assigned to assist in the development of water-supplies along the Alaska Highway in Alaska and Canada and in the solution of problems created by permafrost.

U. S. Geological Survey,
Washington, D. C.

APPENDIX C--GROUND-WATER INVESTIGATIONS IN THE SOUTHWEST

Harry F. Blaney

During the past three years the Division of Irrigation, Soil Conservation Service of the United States Department of Agriculture, has been conducting drainage studies of irrigated lands in Imperial Valley, California, in cooperation with the Imperial Irrigation District and other agencies. Ground-water fluctuations in observation-wells and flow of water from tile drains were measured in problem areas. In 1943-44 the permeability of representative subsoils was measured by field and laboratory methods for the purpose of obtaining data for determining proper spacing and depth of subsurface drains.

The Division, in connection with irrigation and consumptive use of water-studies, continued measurement of ground-water fluctuations in the San Luis Rey Valley, San Diego County, in cooperation with the California State Division of Water Resources and the United States Geological Survey. Early in 1944 investigations on evapotranspiration losses and ground-water fluctuations along the Santa Ana River for several miles below Prado Dam were started in cooperation with the United States Geological Survey and the Orange County Water District for the purpose of determining the quantity of water that might be conserved for irrigation.

Water-spreading investigations were continued during 1943 by the Division in southern California. Active work was started in the spring of 1944 on an investigation to determine the feasibility of recharging depleted ground-water supplies in certain areas in the upper San Joaquin Valley by spreading off-season water which will be available upon the completion of the Central Valley Project. This investigation is being carried on by the Division of Irrigation of the Soil Conservation Service, United States Bureau of Reclamation, State of California, United States Salinity Laboratory, and local agencies.

The United States Geological Survey is conducting ground-water investigations in the Long Beach-Santa Ana, and Santa Barbara areas (California), Safford Valley (Arizona), and several areas in New Mexico. Reports on these areas were made by PIPER, TURNER, and THEIS in the report for 1943 of the Committee [Trans. Amer. Geophys. Union, Part II, pp. 412-417, 1943].

Soil Conservation Service,
Los Angeles, California

APPENDIX D--GROUND-WATER INVESTIGATIONS MADE DURING 1943 BY THE CORPS OF ENGINEERS, UNITED STATES ARMY

Edward B. Burwell, Jr.

Ground-water investigations of a wide belt of north-central Florida were continued in connection with studies being made for a barge canal across Florida. Approximately 160 observation-wells were measured twice monthly. Continuous records are available for these wells covering 1932-43.

Detailed subsurface explorations of a localized area about two miles east of Dunnellon, Florida, wherein a ground-water high or mound exists, disclosed a large lense of dolomite at shallow depths in the Ocala limestone. As the area of ground-water mound is coincident with the area underlain by the dolomite, it appears reasonably certain that the higher-than-normal stand of ground water in this area is due to the lower permeability of the dolomite as compared with the Ocala limestone, rather than to more favorable conditions for recharge. This occurrence is of particular interest, because of its relatively close proximity to Rainbow and other springs of the Withlacoochee River Drainage where heavy outflows of ground water take place.

Investigations were made of ground-water conditions in limestone terranes of the Cumberland River Basin, Tennessee, in connection with the study of leakage possibilities at reservoir-sites. These have emphasized the influence of minor structures in horizontally-bedded limestones on the extent and depth of solution and the importance of structure-mapping in the search for unfavorable reservoir-rim conditions. Folds of small magnitude are often the seat of extensive solution channelling in an otherwise relatively tight formation. At one site where a high dam was built, shifting of the axis a few hundred feet away from a minor fold with a closure of only ten to fifteen feet made the difference between a relatively tight abutment and a cavernous one.

Other extensive ground-water investigations were made by the Corps of Engineers or by other Government agencies for the Corps in connection with war planning, but information on these is not available at the present time.

Office of the Chief of Engineers,
Washington, D. C.

APPENDIX E--PUMPING TESTS CONDUCTED AT KANSAS CITY, KANSAS, BY THE CORPS OF ENGINEERS, UNITED STATES ARMY

V. C. Fishel

A series of pumping tests was made in January and February, 1944, in the heavily industrialized part of the Fairfax District of Kansas City, Kansas, under the supervision of the United States Engineer Office, Kansas City District, Kansas City, Missouri.

The tests were made on a well located approximately 160 feet from the landward toe of the levee along the Missouri River. Thirty-eight observation-wells were constructed in three equally spaced radial lines extending out from the pumped well. The observation-wells in each line were located at distances of 5, 15, 35, 75, and 155 feet from the pumped well. The observation-wells at each of these points were constructed to three different depths roughly representing penetrations of 25, 50, and 75 per cent of the pervious substratum. The pumped well represented a penetration of approximately 70 per cent of the pervious substratum, and a series of pumping tests was performed at this depth. The well was partially plugged at several depths, and the tests repeated at these depths to determine the effects of partially penetrating wells. Each series of tests included pumping the well at different discharge-rates until the water-levels in the observation-wells reached equilibrium.

The observed data are being studied relative to the possibility of effecting a reduction of subsurface pressures which, during periods of flood, might endanger the protective system.

U. S. Geological Survey,
Lawrence, Kansas

APPENDIX F--GROUND-WATER STUDIES IN CENTRAL AMERICA

A. N. Sayre

In June, 1943, the United States Geological Survey assigned two ground-water geologists, A. N. SAYRE and G. C. TAYLOR, Jr., to study water-supply problems in Central America for the Coordinator of Inter-American Affairs and to make recommendations for remedial measures to provide water for cities and towns, especially along the Inter-American Highway. El Salvador, where a large number of towns along the highway have serious water-shortages during the six-month dry season from December to June, was selected as the country in which most of the work was to be done. The Direccion de Sanidad de Salvador, through its Director, Dr. V. A. SUTTER, provided a list of some 35 cities which suffered the most serious water-shortages and each of these cities was visited. The geological and ground-water conditions in the vicinity were studied by reconnaissance-methods and remedial measures were recommended. In nearly every case the water-shortage was due in large part to improper or incomplete development of the available supplies. Most municipalities obtained their water-supplies from springs which either had inadequate flow or were improperly developed. In a few cases the spring-flow was adequate but a large quantity of water was wasted either through poor distribution-systems or through breaks in the line that conducted water from the spring to the city. Nearly all of the water works were unsanitary. In most places it appeared likely that adequate supplies can be obtained from wells at relatively

shallow depth. In some places adequate supplies can be obtained by proper improvements of springs that are now in use. In a very few cases no remedy for the shortage of water could be suggested.

The Government agencies in Salvador expect to follow the recommendations made in various reports transmitted by SAYRE and TAYLOR, but only a few of the projects have been completed to date. However, the results of this work to date have been most satisfactory.

It was believed that the most lasting results could be obtained by attempting to train qualified nationals in the methods of investigation used in the United States. Accordingly, the assignment of two Salvadorian engineers was secured. These men accompanied SAYRE and TAYLOR on all of their trips and assisted in the preparation of reports on the various surveys. One of them, Sr. CARLOS ALEMÁN, has subsequently been assigned to the Departmento de Fomento, which has charge of developing water-supplies and other public works throughout the country, and he is applying the American methods to his work. The other, Sr. Ing. MARIO PACHECO, is employed by the Coordinator of Inter-American Affairs and is also continuing the same general sort of work.

SAYRE and TAYLOR also visited Managua, where an expensive infiltration-gallery was being constructed to supply water to the city. They recommended that construction be stopped until simple investigations to show the probable yield of the gallery could be made. Some wells were dug and pumping tests on them showed that the water-supply obtainable from this gallery would not justify the cost of the gallery. The project was therefore abandoned. Wells will probably be constructed to provide the necessary additional water.

U. S. Geological Survey,
Washington, D. C.

APPENDIX G--GEOLOGICAL AND GEOPHYSICAL STUDIES OF GROUND-WATER GEOLOGY IN ILLINOIS BY THE ILLINOIS STATE GEOLOGICAL SURVEY

M. M. Leighton

Introduction--Geological and geophysical work in connection with ground water is carried on by the staff of the Subsurface Division of the Illinois State Geological Survey. Several different types of work are done in connection with the ground-water supplies of the State. These include: (1) Preparation of reports on the ground-water geology in response to inquiries; (2) electrical earth-resistivity surveys for the location of water-bearing sands and gravels; (3) geophysical logging of water-wells; (4) project studies of ground-water geology of important areas, for publication.

The work of the Geological Survey constitutes only a part of ground-water work done in Illinois inasmuch as chemical and engineering investigations are carried on by the State Water Survey Division, and public-health aspects are handled by the State Department of Public Health. In many problems all three agencies collaborate.

Reports on ground-water geology--All inquiries concerning the ground-water geology or ground-water possibilities at any locations within the State are answered by the State Geological Survey in the form of complete geological reports. These reports include estimates of depths and thicknesses of various formations, descriptions of the aquifers, and the application of the knowledge of geological conditions to the problems at hand. At the same time, parallel reports dealing with the chemical and engineering aspects of the proposed water-supply developments are provided by the State Water Survey. Both types of reports on a single project are transmitted together to the inquirer. A graphic representation of the number and character of these inquiries for the past seven years is summarized in Figure 1. Many of the investigations involve conferences in the office or field.

The original geological information from which ground-water geology reports are written consists of many thousands of well-logs and sample sets of drill-cuttings which have been collected by the Survey staff or filed with the Survey by drillers or well-owners in accordance with the rules and regulations prescribed by law. The Survey cooperates closely with the Illinois Water-Well Drillers Association, and promotes the collection of complete and accurate well data.

Electrical earth-resistivity surveys--The Illinois Geological Survey maintains a geophysical service for municipalities and large industries to assist in the location of water-bearing sands and gravels in the glacial drift by means of electrical earth-resistivity surveys. The instrument used

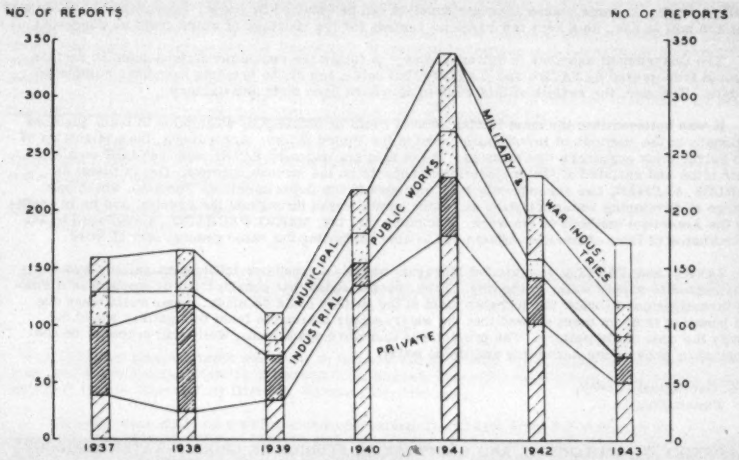

Fig. 1--Number and character of ground-water inquiries received by Illinois Geological Survey during 1937-43

is a modified GISH-ROONEY type assembled by the Survey. It is customary for the Survey to furnish the instrument and operator without charge while the organization to be benefitted furnishes the labor for setting the electrodes. Upon completion of a survey, the data are analyzed and integrated with the available geological information in a report on the particular area. Recommendations for test-drilling based on the interpretation of these data are made. Sample cuttings from test-drilling are examined, and geological cooperation continues until the ground-water supply has been developed.

During the past 12 years 121 electrical earth-resistivity surveys have been made. These range in size from small areas less than a square mile in extent requiring less than 20 stations to large surveys covering 25 or more square miles and requiring nearly 1,000 stations. The results of these surveys are summarized below:

New supplies established or existing supplies augmented as result of favorable recommendations	61
Favorable recommendations, but no action yet taken so far as known	30
Unfavorable report, but testing developed supplies	1
Unfavorable report, tested and failed	12
Unfavorable report, and project abandoned	17
Total	121

During the course of these investigations many valuable data on subsurface geology and geophysics have been obtained. Both data and methods are constantly subjected to scrutiny for possible improvements.

The surveys from which water-supplies were established were run for the following types of installations:

Cities and villages	46	Soybean processing plant	1
Railroads	3	Army cantonment	2
Oil-companies	2	County establishment	1
Schools	2	State establishment	1
Ordnance plants	2	Total	60

It is apparent that these electrical-resistivity methods have been used primarily for the development of municipal water-supplies.

In almost all instances, the resistivity-surveys have effected great savings in the cost of development of water-supply installations over that which would have been necessary if random drilling exploration had been used.

Geophysical well logging--In connection with a project study of the ground-water geology in northeastern Illinois, considerable work was done with geophysical well-logging methods. Most of the deep water-wells in this area are drilled with cable tools and have casing set only to shut out caving sections or prevent entrance of surface contamination. As a result, regular geophysical oil-field logging methods have provided a splendid means of studying the water-production from the aquifers in deep wells in this area. For more than 30 wells, these surveys have integrated the data from the standard electric log (potential- and resistivity-curves), temperature-log, caliper-log, fluid-resistivity log, and current-meter (direction and rate of flow) surveys with available sample-study information for the preparation of "composite geophysical logs." In addition to the tools and methods regularly used in oil-well logging, special adaptations have been made for water-well problems. Experimentation in improving present methods and development of new instruments, techniques, and applications is being carried on, which may permit logging of wells in the glacial drift or may have wider application in various fields of well logging.

The logging of cable-tool water-wells is done in cooperation with the commercial logging-companies. At first an experimental program was carried on by the State Geological Survey to determine the possibilities of the applications of the methods and to obtain basic geological and geophysical data. Since the value of the work was demonstrated, particularly in the applications to old wells as guidance to reworking, the costs of the surveys are now being borne by the well-owners, the Geological Survey providing service including drafting, preparation, and interpretation of the logs.

Geophysical logs of 31 wells were made during 1942, 1943, and the first quarter of 1944, for the following:

Municipalities	12	State institutions	3
Industries	8	Special or experimental tests	3
Ordnance plants	5	Total	31

To date all geophysical logs made for the purpose have permitted successful and economical rehabilitation of the wells.

Several descriptions of the geophysical well-logging work have been published recently [see 1 of "References" at end of Appendix].

Project studies of ground-water geology--Special studies of areas of interest or critical in ground water are made from time to time by the project method. These studies include special reports on the drift thickness or bed-rock surface intended for the use of health authorities in regulating well-construction as in publications of Circulars 92 and 102 [2]. In other instances special studies of the glacial drift and bed-rock surface in areas of water-supply shortage such as Peoria, East Saint Louis, and Joliet [3] districts have been made to determine additional possibilities for development.

A comprehensive subsurface study of the geology of north-central Illinois [4] has been completed. A report on the ground-water geology of northeastern Illinois is in process of preparation. These studies, issued as bulletins, will furnish complete structural and stratigraphic reports of the regions and considerable detailed data on the reservoirs-beds. Other similar studies of the ground-water geology of various areas within the State are planned or are in progress.

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U. S. Geological Survey,
Washington 25, D. C.

REPORT OF COMMITTEE ON THE CHEMISTRY OF NATURAL WATERS, 1943-44

C. S. Howard, Chairman

The membership of the Committee during the past year was as follows:

Stanley W. Lohman, United States Geological Survey, Lawrence, Kansas
Melvin Romanoff, National Bureau of Standards, Washington, D. C.
S. K. Love, United States Geological Survey, Washington, D. C.
C. S. Scofield, Department of Agriculture, Beltsville, Maryland
T. G. Thompson, University of Washington, Seattle, Washington
C. S. Howard, United States Geological Survey, Albuquerque, New Mexico

There has been little activity in the field of this Committee during the past year and there is nothing therefore to report.

U. S. Geological Survey,
Albuquerque, New Mexico

REPORT OF COMMITTEE ON LAND-EROSION, 1943-44

W. C. Lowdermilk, Chairman

The Committee on Land-Erosion, consisting of William H. Hobbs (resigned), C. W. Thornthwaite, and myself, has not had time to do much thus far. The Chairman only recently returned from China when he was informed of the appointment of this Committee. But plans are under way to begin a comprehensive examination of the complex dynamics of land-erosion.

We are pleased to report that in 1941 your Chairman arranged for the Symposium on Dynamics of Land-Erosion for the General Meeting of the Annual Assembly of the American Geophysical Union [see Trans. Amer. Geophys. Union, Part II, pp. 236-320, 1941]. In this symposium, the following papers have laid important groundwork for further development of this subject: (1) Geomorphic aspects of normal and accelerated erosion, by C. F. STEWART SHARPE; (2) Land-erosion--normal and accelerated--in the semiarid west, by REED W. BAILEY; (3) Recent developments in the dynamics of wind-erosion, by FRANK J. MALINA; (4) Dynamics of water-erosion on land-surfaces, by LEONARD SCHIFF and ROBERT E. YODER; (5) Dynamics of entrainment of erosional debris and sedimentation, by CARL B. BROWN; (6) Physiographic engineering: Land-erosion controls, by W. C. LOWDERMILK.

Erosion by ice was not covered in these papers but will also be included within the purview of the Committee's interests.

One of the questions calling for thorough examination by your Committee is: How are normal processes of land-erosion accelerated or lessened by works of man? To answer this question it is necessary, first, to set up criteria of normal processes of land-erosion under different conditions as they occur on land. Methods of measuring rates of the geologic norm of erosion by water and by wind are called for. Here is a field full of interest.

Secondly, it is desirable to measure degrees and rates of acceleration and retardation of erosion brought on by measures in man's occupation of the land. Criteria of such measurements will need to be examined and appraised. The object in this instance is to measure rates and magnitudes of acceleration and retardation of erosion by whatever process.

Thirdly, it is proposed to include within the Committee's activities an examination of the consequences in terms of geophysical phenomena of the acceleration and retardation of erosional processes.

The emphasis here will be chiefly upon measurable effects. But at the same time, within the purpose of the American Geophysical Union, consideration must be given to the operation of these processes as they affect human welfare. For acceleration or retardation of natural processes must affect the capacity of a land-area to support its resident population, and of the Earth to support the human race.

Findings of your Committee will be of interest not only to the scientific world, but we hope to the public at large. The work of your Committee may well make up a volume on this subject that is of lively perennial interest scientifically, but is also vital to human welfare. Your Chairman presented and discussed views of erosion as he found them in the great loessial region of China on the recent survey of Northwest China.

U. S. Soil Conservation Service,
Washington 25, D. C.

PROGRESS REPORT OF SPECIAL COMMITTEE ON HYDROLOGIC REGIONS OF THE UNITED STATES, 1943-44

Robert E. Horton, Chairman

Introduction--The Special Committee on Hydrologic Regions, appointed as a result of resolution of the Executive Committee, Section of Hydrology, American Geophysical Union, June 23, 1943, was charged with duties summarized briefly as follows: (1) To coordinate past and present work relating to this subject; (2) to stimulate interest in the subject; and (3) to formulate and disseminate needs for study and classification of areas on the basis of hydrologic characteristics. Some of these objectives could be continued indefinitely. Others can be covered by a report. This is a Special Committee and it is assumed that it will cease to exist with the submission of its report.

Only the Chairman of the Special Committee on Hydrologic Regions has thus far been appointed, for the reason that until work of the previous Committee and of the Chairman had been compiled, there was little to lay before additional members for consideration.

Previous work--The climatic and hydrologic characteristics of a region are interrelated and as a result much of the extensive work so far performed with reference to climatic classification, starting with DE MARTONNE, has a bearing on hydrologic classification.

Various maps and atlases hitherto prepared also have a bearing on the subject in hand. These include, for example, The atlas of American agriculture, various maps of the United States, contained in the Year Book of the United States Department of Agriculture, 1931, and the climatic maps of North America, by BROOKS and GEIGER. More specifically, with reference to attempts to subdivide the United States into hydrologic regions, the following work was antecedent to that of the present Committee:

In 1937 Dr. W. C. LOWDERMILK, then Chief of the Research Division of the Soil Conservation Service, requested the appointment of an Advisory Committee on Research by the Section of Hydrology of the American Geophysical Union, this Committee to act as an Advisory Committee to the Research Division, Soil Conservation Service. Action was taken at the meeting of the Advisory Council of the Section at Denver in 1937 and a Committee appointed by President SHERMAN, as follows:

Dr. J. E. Church, University of Nevada, Reno, Nevada
W. W. Horner, 803 Shell Building, Saint Louis, Missouri
A. F. Meyer, 284 Baker Building, Minneapolis, Minnesota
C. M. Saville, Board of Water Supply, Hartford, Connecticut
L. K. Sherman, 53 West Jackson Boulevard, Chicago, Illinois
Samuel Shulits, Charleston, South Carolina
Roy N. Towl, Omaha, Nebraska
Dr. F. J. Veihmeyer, University Farm, Davis, California
Robert E. Horton, Chairman, Voorheesville, New York

One of the questions submitted to this Committee for consideration by Dr. LOWDERMILK was the preparation of a map or other basis of subdivision of the United States into hydrologic regions, particularly with reference to determining and delimiting areas on which different types of remedi-

al measures might be needed in relation to erosion-control and soil-conservation.

It was recognized that the hydrologic classification of terrain in respect to one purpose or with respect to one phase or aspect of the hydrologic cycle might be quite different from the classification appropriate to another aspect. Classification with reference to soil-erosion problems, in particular, involves factors such as infiltration-capacity, rainfall-intensity duration and seasonal distribution, flood-producing capability of the region, vegetal cover, natural or artificial, extent to which the land is under cultivation, and certain physical characteristics of the soil, such as its resistivity to erosion.

It was realized that the problem was too broad and complex to be handled by the Advisory Committee as a whole, especially in view of the fact that the work of the Committee was carried on chiefly by correspondence and meetings were impracticable. Accordingly the Chairman of the Advisory Committee undertook to act as a special committee on Hydrologic Regions and H. R. LEACH, then in charge of surface-runoff investigations of the Soil Conservation Service, under C. E. RAMSER, was assigned to cooperate with the Committee in this matter. As a first step an effort was made to compile, on the same scale, maps then available giving data in relation to various factors which might serve as a basis for regional classification. The boundaries of each major region on a given map were transferred to tracing cloth, thus providing a series of maps, two or three of which could be superposed and studied together with reference to delimiting regions within which certain characteristics prevailed. Maps studied in this way included, among others:

Natural vegetation of the United States (Atlas of American agriculture)
MARBUT'S map of major soil-provinces of the United States (Atlas of American agriculture)
Soil Conservation Service map of provisional problem areas in soil-conservation research
Map of the principal drainage-basins of the United States
Map showing THORNTHWAITE'S climatic provinces of the United States
United States Forest Service map of natural vegetation of the United States
Various rainfall- and temperature-maps, and a special map prepared by H. R. LEACH, based on data in Water-Supply Paper 771, showing the average number of calendar days per year with flood-discharges above assumed base-flood magnitude

A comparative study of these various maps in the manner described revealed that while there were certain conspicuous interrelations between data shown on different maps, many things were needed as a basis for delineation of hydrologic regions which were not then available.

Classification of lands on the basis of hydrologic characteristics should obviously take into account several factors, including: (1) Rainfall; (2) total runoff; (3) infiltration, soil-moisture and water-losses; (4) surface-runoff and flood-productivity; (5) ground-water runoff and stream regularity, or regimen.

Infiltration-capacity was felt to be the most important missing factor, as it is closely related to soil-erosion and conservation, flood-productivity, soil-moisture and ground-water flow. At the time this work was undertaken in 1937, data on infiltration-capacity were extremely meager, few areal determinations of infiltration-capacity had been made and the sprinkling infiltrometer for use on natural plats had only recently been developed at Colorado Springs.

With a view to mapping soil-characteristics in some way as closely related to infiltration-capacity as possible, a meeting was held at College Station, Texas, in January, 1938, at which several soils men and representatives of the Soil Conservation Service were present, together with H. R. LEACH and ROBERT E. HORTON. After outlining the problem the conclusion was reached that a map that would at least reflect ranges of values of infiltration-capacity could be prepared from existing, and mostly unpublished, data available at the various agricultural experiment stations throughout the United States. Dr. A. J. CONNER, of Texas Agricultural Experiment Station, offered to undertake the assembling and compiling of these data provided the necessary clearance and cooperation between the Soil Conservation Service and the Office of Experiment Stations was obtained. Results of this meeting were outlined in a letter to Dr. LOWDERMILK, with strong recommendations on the part of the Advisory Committee that the project be immediately put into effect. Shortly thereafter Mr. LEACH'S health began to show weaknesses which presaged his untimely death, and Dr. LOWDERMILK went to the Orient. In the course of these studies both LEACH and the writer became strongly imbued with the idea that it is not practicable to subdivide the country into regions in each of which all the hydrologic characteristics will be alike. Two regions may be alike with respect to some one component of the hydrologic cycle, such as surface-runoff or flood-productivity, yet dissimilar with respect to other components, such as ground-water runoff, susceptibility to erosion, and water-losses.

Voorheesville, New York

REPORT OF COMMITTEE ON RUNOFF, 1943-44

W. G. Hoyt, Chairman

The Committee on Runoff is composed of: Bertram Barnes; Merrill Bernard; Howard L. Cook; E. S. Cullings; G. A. Hathaway; C. R. Hursh; Karl Jetter; Phillip Light; Norbert H. Leupold; Charles C. McDonald; F. T. Mavis; L. K. Sherman; Waldo E. Smith; F. F. Snyder; and H. G. Wilm.

During the year C. R. HURSH was appointed Chairman of the Sub-Committee on Subsurface Flow and GAIL A. HATHAWAY was appointed Chairman of the Sub-Committee on Floods. These two Sub-Committees were formed at the request of President CHURCH of the Section. HOYT and HURSH submit brief reports respectively, on flood- and drought-events and on subsurface-flow (Appendices A and B). It is expected that the Sub-Committee on Floods will interest itself not only, with the hydraulics and hydrology of so-called widespread floods but also with the hydraulics and hydrology of the local flash-flood. The Sub-Committee on Subsurface Flow will interest itself in the movement of water through the ground and into the streams.

As pointed out in my report last year the war has resulted in a change in emphasis with respect to hydrologic research. More and more emphasis is being placed on problems relating to war-activities and on problems which affect our present National economy. In the field of runoff-research both the Soil Conservation Service and the Forest Service have had to reduce some of their field-activities. In my report last year, with respect to the Soil Conservation Service I reported that runoff-measurement operations at all field-stations were being continued as heretofore but that in general observations of runoff from small agricultural watersheds had been terminated. I should have reported that at three stations, namely, Clarinda (Iowa), Bethany (Missouri), and Tyler (Texas), observation of runoff from small agricultural watersheds had been terminated. WALDO E. SMITH reports for this year that a good many of the stations hitherto in operation have been continued, but curtailment in operations, shortage in personnel, or completion of investigations has caused a number of stations to be closed down. These include those at Mexican Springs (New Mexico), Moscow and Emmett (Idaho), Newberg (Oregon), Vaga (Texas), Santa Paula and Watsonville (California), and Freehold (Missouri). In addition, the runoff-measurement work at Waco (Texas) has been drastically curtailed and partial curtailment has taken place at other stations. No further numbers of Hydrologic Bulletin series have been published by the Soil Conservation Service during the past year, but tabulations of the data are continuing, and it is expected that these data will be made generally available at the end of the war. However, a second and final supplement to SCS--RP--39, entitled "Compilation of rainfall and runoff from the watersheds of the Shelby loam and related soils, Conservation Experiment Station, Bethany, Missouri, 1942", by A. W. ZINGG has been released covering the final year of operation of the Bethany Station.

An indication of the change in emphasis is evidenced by the fact that the Public Roads Administration, Federal Works Agency, is taking increasing interest in problems of runoff and flood-flow as evidenced by the fact that a joint research-project undertaken in cooperation with the Soil Conservation Service has as its goal the establishment of the fundamentals of overland-flow. One report on this work by C. F. IZZARD and M. T. AUGUSTINE was published in the Transactions of 1943 [pp. 500-511], and another presented by C. F. IZZARD at the present meeting of the Section indicate the marked progress being made [Part VI, pp. 959-968 of the present Transactions].

The United States Weather Bureau and the Corps of Engineers, working through the Hydrometeorological Section, are making substantial progress in studies and correlations, having as their purpose, (1) the forecasting of storm-events and (2) the forecasting of flood-runoff. These studies are absolutely essential if the most beneficial use is to be made of the storage-capacity in multiple-use reservoirs and in connection with the operation of all reservoirs which combine storage-water for power and irrigation with storage for flood-control.

During the past year further studies of seasonal runoff have been made by the United States Weather Bureau based on precipitation-temperature-runoff relations for a number of watersheds in the western mountains. The initial results of the investigations are published in a paper by LIGHT and KOHLER entitled "Forecasting seasonal runoff by statistical methods" [Trans. Amer. Geophys. Union, Part II, pp. 719-736, 1943].

Forecasts were issued this season for the Platte, Colorado, Rio Grande, and Columbia watersheds. These are incorporated in the following Weather Bureau publications:

Watershed	No. forecast points	Forecast date	Publication
Platte	3	May 1	Snowfall and temperature bulletin, Denver, Colorado
Upper Colorado	8	May 1	Snowfall and temperature bulletin, Grand Junction, Colorado
Upper Rio Grande	7	May 1	Snowfall and temperature bulletin, Albuquerque, New Mexico
Columbia	21	Apr. 1	Climatological data, Oregon

In addition to volume-forecasts for the period April to July in all watersheds, predictions were made at several locations in the Columbia Watershed of crest-stages and discharges and approximate dates of crest.

Collection of meteorologic and hydrologic data is being continued by the Forest Service at the Intermountain Forest and Range Experiment Station in Utah, the Rocky Mountain Forest and Range Experiment Station in Colorado, and the Appalachian Forest Experiment Station in North Carolina, and perhaps at other stations. Interesting papers are being presented at the present meeting on various phases of work at these stations.

Personnel in the Corps of Engineers are working on hydrologic problems under the general direction of G. A. HATHAWAY, member of the Committee on Runoff. These continuing studies relate to flood-flow analysis, unit-hydrographs, flood-routing, and related problems incident to the operations of flood-control reservoirs and disposition of flood-flows. Problems incident to the operation of multiple-use and flood-control reservoirs are reported by HATHAWAY as being of prime concern.

HOWARD L. COOK reports on four items as follows:

(1) The flood-control-survey program of the United States Department of Agriculture has been suspended for the duration and the organization disbanded. Unfinished reports have been set aside for completion after the war. Reports on 18 of the earlier surveys have been submitted to Congress. Of these, 11 have been published as House Documents. These reports contain considerable information on flood-runoff and the factors that influence floods.

(2) The hydrologic research-programs of the Soil Conservation Service and the Forest Service are continuing, although on a somewhat reduced scale.

(3) Some runoff-studies are being made in connection with the Meramec Cooperative Investigation. This investigation was originally sponsored by the National Resources Planning Board and after the demise of that organization was voluntarily continued by the agencies involved. These include: War Department; Federal Power Commission; United States Public Health Service; Fish and Wildlife Service; United States Bureau of Mines; Bureau of Agricultural Economics; Soil Conservation Service; Forest Service; Farm Security Administration; United States Geological Survey; Missouri Conservation Commission; College of Agriculture of Missouri University; Missouri Resources Board. An important purpose of the cooperation is to arrive at a truly comprehensive program for the Meramec Basin of Missouri--a watershed of many and difficult problems. But an even more important objective is to develop a "technique of cooperation" through which all Federal and State agencies interested in watershed-programs will be able to work together in the design of unified programs.

(4) The outstanding development of the year has been the rapid spread of the concept that on thin-soiled watersheds of limited storage, floods often contain large proportions of subsurface flood-runoff and that this constitutes a severe limitation upon the effectiveness of land-treatment for the reduction of flood-runoff.

F. T. MAVIS, member of the Committee and head of the Department of Civil Engineering, Pennsylvania State College, reports of studies relating to the development of a new type of gaging-station for small streams. This work was carried on by Professor JAMES R. VILLEMONTE, now Lt. (j.g.) Naval Reserve, on temporary leave. A description of VILLEMONTE'S investigations is published in Engineering News-Record [issue of November 18, 1943].

There is also included as a part of the report of the Committee on Runoff a description of flood- and drought-events as measured by excessive and deficient stream-flow during the 40-month period January, 1941, through April, 1944. The significance of these events is discussed briefly.

In general water-activities in the United States Geological Survey have been carried on with little, if any, reduction. This healthy situation has resulted from demand on the part of cooperating agencies for continuation of the regular stream-gaging program and by reason of requests from

the War Department and other agencies for special services and reports in connection with surface- and ground-water supplies. No attempt is made herein to list the specific examples.

When Dr. CHURCH became President of the Section of Hydrology, he would not accept my resignation. I felt then, as I do now, that there should be a change in the chairmanship of the Committee on Runoff. Dr. CHURCH has finally consented to accept my resignation, and consequently this is my last report as Chairman. I wish at this time to thank all present and past members of the Committee on Runoff for their hearty cooperation. Dr. CHURCH has appointed R. W. DAVENPORT, who is well known to most members of the Section, to fill out my unexpired term. I anticipate that Chairman DAVENPORT will bring to the Committee many new points of view and the Section will be assured of constructive leadership in the field of runoff.

U. S. Department of the Interior,
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APPENDIX A--FLOOD- AND DROUGHT-EVENTS

W. G. Hoyt

Flood-events, January, 1941, through April, 1944

Forty-four more or less distinct flood-events are listed chronologically in Table 1. A flood-event as used herein is a flood of such magnitude as to be newsworthy. Any event may or may not have been associated with a single meteorological disturbance. It will be noted on Figure 1 that these events occurred during three more or less distinct periods and frequently are grouped on an areal basis. Twelve of the events occur between March and November, 1941, 28 between March, 1942, and August, 1943, and three during January, February, and March, 1944. There was almost a complete absence of flood-events during 18 of the 40 months. Nation-wide, December, 1942, was the wettest with respect to departure of stream-flow from normal. Seven of the 44 flood-events were associated with high temperatures, melting snow, and rain. Fourteen were widespread and record-breaking and confined most generally to the central and southeastern states. The remaining 23 events were generally of a local nature but many broke existing records. Geographically the largest number of events were in the central part of the United States embracing Oklahoma, Kansas, Missouri, and Iowa and adjacent areas, and another is now in progress (May, 1944). Oregon was an exception so far as the West was concerned, with continuous flood-events from November, 1942, to April, 1943. Events No. 36 (May, 1943) and 44 (April, 1944) are probably of greatest National importance and Nos. 19 and 20 (July, 1942) and No. 41 (August, 1943) of greatest local importance and are of special significance in that precipitation-rates may have set new limits for storm-magnitudes.

The grouping of months of excess runoff and flood in the north central States during 1942, 1943, and 1944 to date seems significant. In general the runoff in North and South Dakota, Minnesota, Wisconsin, and Iowa for 30 or more consecutive months was normal or above. Prior to 1942 the last really wet year was 1929 (an intervening period of 12 dry years). In the south central States there seems to have been a decided tendency for the stream-flow to be either deficient or excessive. For example, in Oklahoma and Kansas for the 40 months analyzed, the flow of index-streams has been excessive about 20 months and unusually deficient for eight months (generally consecutive).

The occurrence of the two record-breaking floods in the central States within a period of a year (May, 1943, and April, 1944) will give students of probability something to think about since both floods are being referred to in the technical press as 100-year floods (Table 1, pp. 740-741).

Drought-events
(As measured by deficient stream-flow)

As shown on Figure 1, areas of deficient stream-flow (less than 25 percentile) group themselves into five general drought-events as follows:

Event No. 1-- For the 16 months January, 1941, through April, 1942, subnormal stream-flow persisted throughout most of the States east of the Mississippi River except Florida. In Mississippi the drought persisted for almost 38 months (until March, 1944), in Tennessee and Kentucky 19 months (until August, 1942), and in New England about 28 months (until June, 1943).

Table 1--Flood-events in the United States, January, 1941, through April, 1944

No.	Year and month	Region and remarks
1	1941, February	Connecticut--Minor from melting snow and rain
2	1941, March	Arizona--Minor on Gila River
3	1941, April	Missouri (southwest), Arkansas, Kansas (southeast), Oklahoma (east)--Outstanding on Gasconade and Osage rivers
4	1941, May	California (south-central valley) and New Mexico--melting snow and rain
5	1941, June	Oklahoma, Kansas, Missouri, Iowa--Outstanding and widespread
6	1941, August	Wisconsin (northern)--Local but unprecedented
7	1941, August	Kansas--Local but notable near Parsons
8	1941, September	Missouri, Oklahoma, Kansas, Texas, New Mexico, Arizona--Major proportion and widespread
9	1941, October	Iowa, Montana, Oklahoma, Kansas, Missouri, Arkansas, Texas--Widespread with many records broken
10	1941, October	Colorado River Basin--Major fall flood, Colorado River
11	1941, November	Arkansas, Oklahoma--Notable in both States
12	1941, November	Oregon--Centered in Willamette River Basin
13	1942, March	Michigan (southern), New York (western)--Outstanding and record-breaking
14	1942, April	Louisiana, Arkansas, Texas, Oklahoma, Kansas, Colorado, New Mexico--Widespread and records broken locally
15	1942, May	Minnesota, Wisconsin, North and South Dakota, Montana, Idaho, Oregon--Floods associated with high temperatures, melting snow, and rain
16	1942, May	New York, New Jersey, Pennsylvania, Maryland, Virginia, West Virginia--Notable in eastern parts; special report covering events in Pennsylvania published by the State
17	1942, June	Maine, New Hampshire--Of notable proportions
18	1942, June	South Dakota, Iowa, Missouri, Kansas, Oklahoma--Widespread and of major proportions
19	1942, July	New York, Pennsylvania--Maximum precipitation of record in Allegheny River Basin; special report published by State of Pennsylvania; United States Geological Survey is assembling data for publication; many reports concerning this flood probably will be published in technical papers
20	1942, July	Kentucky (eastern), Virginia (western)--Very outstanding but local
21	1942, July	Texas--Unusual in the southern part
22	1942, July	Minnesota (southern), Illinois (southwestern), Missouri (eastern), Michigan (northern), Wisconsin (northern), Iowa (northwestern)--Severe but generally local
23	1942, August	New York (central), New Jersey (north-central and northeastern), Pennsylvania (eastern), Virginia (northern), Michigan (northern), Nebraska (southeastern), Kansas (eastern), Iowa (northwestern), Oklahoma (central)--Many local and outstanding events
24	1942, September	New York (eastern), Wisconsin (central), Minnesota (southern), Iowa (western), Kansas (western), Arkansas (southwestern), Oklahoma (southeastern), Texas (southern), New Mexico (eastern)--Many local and outstanding events

Table 1--Flood-events in the United States, January, 1941, through April, 1944 (concluded)

No.	Year and month	Region and remarks
25	1942, October	Virginia, West Virginia, Maryland--Of major proportions and record-breaking in Potomac and Rappahannock River basins
26	1942, October	Arkansas--Local but outstanding in northwestern part
27	1942, November	Oregon--General and outstanding in Willamette River Basin
28	1942, December	Pennsylvania, West Virginia, Ohio, Kentucky, Tennessee, Alabama--Widespread early winter flood
29	1942, December	Oklahoma, Arkansas, Kansas, Missouri--Rather widespread flood associated with rain and melting snow
30	1943, January	California, Oregon, Nevada, Idaho--Rain and melting snow; generally minor except in Oregon
31	1943, February	Nevada, Oregon, Idaho, Montana, North Dakota, South Dakota, Minnesota, Iowa--Ice-jams and floods associated with rain and melting snow; record-breaking in Nevada
32	1943, March	Ohio, Indiana, Kentucky, Tennessee, Alabama, Mississippi, Louisiana--Widespread and noteworthy floods
33	1943, March	North and South Dakota--Floods associated with a chinook and ice-jams
34	1943, March	Oregon--Three general storms
35	1943, April	Oregon, Nevada, Idaho, Montana, North and South Dakota, Minnesota, Missouri, Nebraska--Floods generally associated with rain and melting snow; record-breaking on Missouri River
36	1943, May	Oklahoma, Arkansas, Kansas, Missouri, Illinois, Indiana, Michigan--Widespread general flood of major importance; United States Geological Survey is assembling data for publication
37	1943, June	Montana, Minnesota, Wisconsin, Iowa, Missouri, Nebraska, Kansas, Texas--Quite widespread and noteworthy
38	1943, June	Maine, Vermont, New Hampshire--Some records broken in northern Vermont
39	1943, July	Iowa, Minnesota--Local and minor
40	1943, August	Iowa, Illinois, Minnesota--Local but noteworthy
41	1943, August	West Virginia--Local but outstanding; precipitation record-breaking; major catastrophe so far as loss of life is concerned (No. 23)
42	1944, February	North Carolina, Kentucky, Illinois--Generally record-breaking
43	1944, March	Georgia, Alabama, Mississippi, Texas, Arkansas, Oklahoma, Indiana--Local but noteworthy
44	1944, April	North and South Dakota, Indiana, Illinois, Iowa, Kansas, Nebraska, Arkansas, Oklahoma, Georgia, Florida, Mississippi--Widespread, notable, and record-breaking, especially in central States; this flood-event and that of May 1943 (No. 36) are being referred to in the technical press as two 100-year floods that have occurred in the same general locality within a year

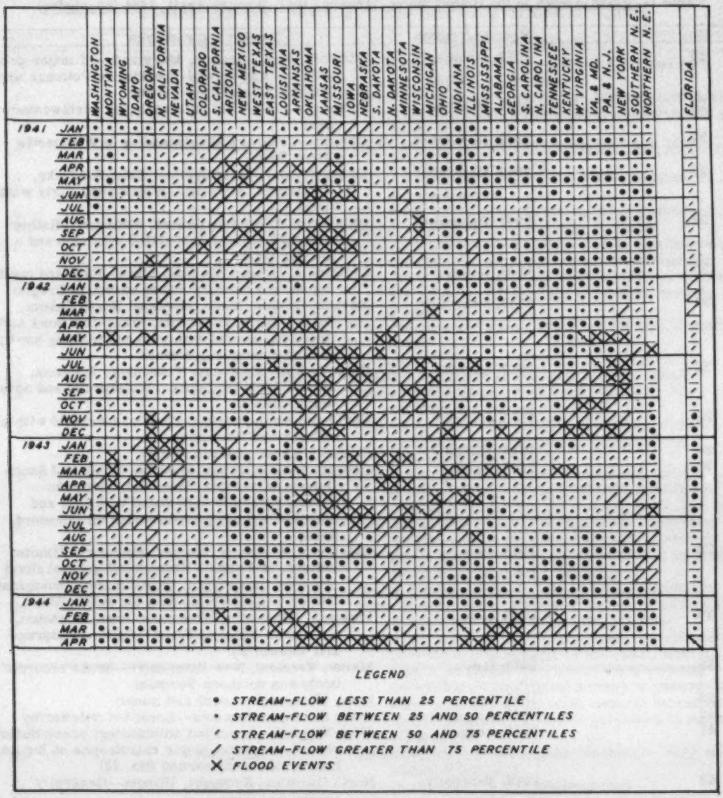

Fig. 1--Deficient and excess stream-flow, January, 1941, through April, 1944

Event No. 2--Drought-event No. 2 was almost a continuation of drought-event No. 1. Beginning during August and September, 1943, stream-flow was again deficient throughout the States east of the Mississippi River and continued uninterruptedly through February, 1944, when it seemed to have been broken except in New England and possibly New York.

Event No. 3--Those who have followed the maps in the Water Resources Review, United States and Canada, issued monthly by the Geological Survey of the United States Interior Department (it is hoped that all who are vitally interested in water-resources are availing themselves of the opportunity of receiving this Review monthly), will have noted that stream-flow in relation to normal in Florida, and especially the southern part, does not always correspond with stream-flow in adjacent areas. For example, for more than half of the time when stream-flow in Georgia was above normal, stream-flow in southern Florida was below normal, and vice versa. For this reason Florida has been listed separately on Figure 1. A period of deficient stream-flow which has persisted in southern Florida for 19 months since November, 1942, is listed herein as drought-event No. 3.

Event No. 4--Geographically, drought-event No. 4 embraces Arizona, New Mexico, Texas, Louisiana, Arkansas, Oklahoma, and Kansas. In west Texas, New Mexico, and Arizona stream-flow has been generally deficient for 22 months and as of September was still in progress. In the remainder of the area the drought lasted for only 13 months (January, 1943, to January, 1944).

Event No. 5--This drought-event should perhaps be listed as a semi-drought event in that stream-flow in the northwestern States has been generally subnormal more often than actually deficient. In parts of the area, however, especially in the Columbia River Basin, there has actually been a stream-flow drought and there are indications that stream-flow may continue subnormal and perhaps deficient for a considerable period.

Drought-events Nos. 1, 2, and 3 are continuations of periods of deficient stream-flow in the eastern States beginning about 1940. Nineteen hundred and forty-two had the fifth driest index since 1910, 1941 the third driest in the northeastern States, and 1940 the fifth driest, and 1941 the second driest in the southeastern States [see HOYT and LANGBEIN, "Yield of streams as a measure of climatic influences", Geog. Rev., April, 1944].

Drought-event No. 4 is in contrast to water-years 1941 and 1942, which were, respectively, the wettest and the fourth wettest since 1910 in the south central States and quite generally throughout the Southwest.

Drought-event No. 5 is more or less a continuation of a dryness that extends back to the thirties. The Northwest has not experienced a really wet year since 1928. With 1942, a slightly above-normal year, it is a safe bet that most everyone would have gambled that it was the beginning of a series of wet years.

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APPENDIX B--REPORT OF SUB-COMMITTEE ON SUBSURFACE-FLOW

C. R. Hursh, Chairman

The full membership of the Sub-Committee on Subsurface-Flow has not yet been completed and will be announced later. The two accompanying statements have been prepared during the past year to serve as a general introduction to further discussion.

Subsurface-Flow

C. R. Hursh

The following review does not attempt to cover the literature on the development of current concepts of subsurface-flow. It will only serve as an elementary guide for anyone wishing to inquire further into the subject.

Interpretation of surface-runoff phenomena, and more particularly the movement of water after it has reached river-channels, has been the subject of much excellent research by HORTON, SHERMAN, and others. Interpretation of flood-hydrographs from areas of high soil-infiltration where there is little, if any, surface- or overland-flow, has received less attention. In southern California flood-phenomena have been described [see 1 of "References" at end of Appendix] that could not be explained without assigning a considerable amount of the flood-volume to subsurface return-flow of water. During the past year HORNER [2] has reemphasized the importance of stream-channel inflow that takes place during the storm-period from areas of high infiltration where overland-runoff is of little significance. HORNER points out that it is imperative that we understand this source of storm-water in order to properly interpret the role of land during flood-periods. COOK [3] has also stated that some of the most difficult hydrologic problems with which the Department of Agriculture Flood-Control-Survey organization has had to deal have arisen from "attempts to estimate the effect of treatment of land upon floods from areas in which the capacity of the soil-mantle to store infiltrated water is so small that a substantial proportion of the volume of damaging flood-flows is derived from subsurface-runoff".

The need for better methods for differentiating ground-water runoff and surface-runoff in the stream-flow hydrograph was specifically pointed out by the National Resources Committee [4] as

one of the important deficiencies in hydrologic research. However, HOYT and others [5] had previously emphasized the difficulties in drawing a ground-water hydrograph under a complex storm-hydrograph. One of these difficulties lies in taking cognizance of the storm-water that reaches the stream-channel after a short period of temporary detention storage within the soil-profile.

In 1934 LOWDERMILK [6] expressed the idea that a dynamic form of subsurface storm-flow is associated with certain soil-profiles, which is neither true overland storm-runoff nor true ground-water discharge. This type of flow he considered to be shallow seepage or discharge of wet-weather springs. Discussing this runoff-phenomenon in 1936 the writer [7] proposed the term subsurface storm-flow for the dynamic type of storm-water that enters the soil but moves away from the area through upper soil-horizons at a rate much in excess of normal ground-water seepage.

In his theory of maximum ground-water levels, HORTON [8] has introduced an essential assumption to the concept of subsurface storm-flow. His assumption is that topographic conditions such as gullies and natural drainage-lines may create temporary outlets for the ground-water aquifer at the upper limits of the rise of the water-table.

On sloping land and for natural soil-profiles with strongly differentiated horizons, the writer believes that another factor limiting the rise of the water-table is the tremendous increase in lateral transmission-rate as the water-table approaches the soil-surface. Studies employing numerous observation wells in the high rainfall-belt of the southern Appalachian Mountains tend to substantiate this theory [9]. In considering flow through natural upper soil-horizons, the formulas of soil-mechanics do not generally apply. Here porosity is not a factor of individual soil-particle size, but rather of structure determined by particle aggregates which form a three dimensional lattice-pattern. This structure is permeated throughout by biological channels which in themselves also function as natural hydraulic pathways [10]. A single dead-root channel, worm-hole, or insect-burrow may govern both the draining of water and the escape of air through a considerable block of soil. In the subsoil, less influenced by biological activity, water-movement is more directly related to soil-particle size and the formulas of soil-mechanics more nearly apply. These concepts have been developed recently in this country through the researches of BAVER [11], SLATER [12], and others.

The soil-profile must be viewed as an entity made up of definite horizons, a concept that is also of fairly recent origin. It was probably not till the appearance of MARBUT'S translation in 1927 of GLINKA [13] on soils and their development that the natural relations of soil-horizons became the basis of pedologic thought throughout the United States. The hydrologic significance of different soil-horizons as related to storage and movement of water still offers a valuable and relatively unexplored field for research. Herein lie some of the most critical of the practical problems of land-use hydrology, water-control on the land, and watershed-management.

RIESBOL [14] has presented a summary of the aspects of subsurface-water in hydrologic research on agricultural watersheds. He concludes that inflow to a ground-water reservoir, already nearly filled, will return to the surface as effluent seepage to become a factor in the flood-hydrograph not only from small watersheds but from larger stream-drainages as well. HOYT [15] has expressed himself that after prolonged rain when natural storage has already become utilized, subsurface storm-flow may under some conditions reach the stream-channels nearly as promptly as overland storm-runoff.

BARNES [16] has been one of the first to make a practical application of the concept of subsurface-flow to runoff-phenomena. Using a graphical analysis he has presented a method for separating the components of storm-flow as surface-flow, storm-seepage, and ground-water.

It would be expected that rises in water-tables normally close to the soil-surface, would indicate that field-moisture deficiencies have been satisfied and that further rainfall will contribute directly to ground-water available for stream-flow. This idea was expressed by THOMPSON [17] as follows: "The question may be raised as to whether fluctuations of the water-table may also be used to show danger of flood conditions when heavy rains produce an unusual saturation of the ground." This is a suggested application of the general theory that maximum aquifer storage is directly related to maximum ground-water discharge. SNYDER [18] has made a practical application of this theory by introducing the use of the ground-water storage-curve. This curve is derived from the curve of ground-water depletion which has an accelerating rate as its upper limits are approached. It appears to the writer that the upper limits of the ground-water depletion-curve

approaches or merges into the rapid rates of subsurface storm-flow. PARKER [19], and much earlier VERMULE [20] both discuss maximum ground-water discharge in terms of the maximum water-storage during spring months. Consequently, for a given amount of rain, floods are more likely to occur in the spring months than any other season because at this time storage-opportunity is at a minimum for temperate semi-humid climates. For humid climates, the soil-profile may conceivably function very much as a natural reservoir [21] for the temporary detention of storm-water as well as for the more permanent storage of ground-water that will ultimately become the base-flow of streams.

The importance of understanding subsurface-flow is to better interpret the hydrograph of stream-flow. Specifically, it will aid materially in interpreting the relation of the recession-curve of the storm-hydrograph to the curve of normal ground-water depletion. This will facilitate in relating watershed-management to stream-behavior. Recognition of conditions under which subsurface-flow does appear might aid in the selection of individual storms serving the unit-hydrograph most applicable for different conditions of storage present within the drainage-basin prior to any current storm.

There are several conceivable explanations that might account for subsurface-flow. One is the rapid spilling of the over-charged ground-water aquifer through extremely porous upper soil-horizons. Another is the relatively shallow penetration of storm-water into porous upper soil-horizons and its rapid lateral flow with the slope to natural outlets. In the first case, the water-table is close to the soil-surface and its position becomes an important factor. In the second case, the true water-table may have no part in the phenomenon.

WENZEL [22] has suggested that the increase in stream-discharge from subsurface-flow may result from the saturated cross-sectional area of the stream-bank. In areas of irregular topography there is a rapid accumulation of infiltrated storm-water in porous colluvial ravine fills and terraces that discharge directly into the stream-channel. The rapid increase of ground-water near the stream comes from subsurface-flow on slopes above the colluvial fills. The result is not only an increase in cross-sectional area through which water enters the stream, but principally in a sharp increase in the slope of the water-table at the stream-edge. Subsurface-flow under the above conditions should not be confused with subsequent return of temporary bank-storage that has taken place from the stream during periods of bank-full stage. Return from bank-storage takes place at a greater rate than normal ground-water depletion and on this basis it may be considered to be a form of subsurface-flow.

One of the handicaps in interpreting the nature of subsurface storm-flow has been the lack of records from suitable experimental basins. This handicap is being overcome through such co-operative studies as those conducted on the Ralston Creek and Rapid Creek basins at the University of Iowa. Other studies yielding suitable data for interpreting the nature of stream-flow are being conducted by the United States Forest Service of the Department of Agriculture on the Coweeta Experimental Forest in the high rainfall-belt of the southern Appalachian Mountains, in Colorado, and in southern California. The Soil Conservation Service has likewise obtained runoff-records from small drainage-areas on the Coshocton Experimental Area in Ohio, and elsewhere. All of these studies will aid materially in furnishing basic records from areas of known hydrologic characteristics. It is to be hoped that these and further intensive studies may contribute to better understanding the nature of subsurface-flow.

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Subsurface-Flow

Bertram S. Barnes

It is generally recognized that the nomenclature of subsurface-flows is not satisfactory. We may expect that a more suitable terminology will not be adopted until the nature of quick subsurface-runoff is better understood. There are several gaps in our knowledge to be bridged before this type of discharge can be established as a simple flow resulting from a known set of conditions, or as the total of a number of flows showing similar behavior but produced by different causes.

The writer has found that the recession-characteristics of quick subsurface-runoff are of great practical value in the separation of ground-water flow from the hydrograph of stream-discharge. Various studies, especially those of HORTON, HORNER and FLYNT, and R. T. ZOCH, have shown that in headwater-areas where evaporation from stream-surfaces and transpiration from the banks is relatively small, the depletion-curves of overland-flow and of ground-water discharge may both be defined by equations of the form

$$Q = Q_0 k^t$$

where Q_0 and Q are values of the discharge separated by a time-interval t. Hydrographs of natural stream-flow cannot usually be divided into two elements having this form of recession, but most of them may readily be separated into three such elements. The recession-characteristics of the middle or intermediate element are highly useful in the graphical separation of ground-water flow. In this procedure it is not necessary to separate the element of overland-runoff, because the value of k for the intermediate element is determined during periods when the overland-runoff is negligible. The writer has used the term "interflow" for the intermediate element in order that its recession-slope can be used as a tool without inviting a controversy regarding its source.

The total volume of ground-water in live storage bears a simple relationship to the rate of ground-water discharge. The comparison of observed rates and losses of infiltration with computed values of the volume of ground-water recharge might yield valuable knowledge of the nature of subsurface-runoff.

It is desirable to learn to what extent bank-storage can produce subsurface-flows. L. K. SHERMAN has approached this problem by comparing estimated values of bank-storage capacity at different stages with the subsurface-runoff. An attempt was made at the University of Iowa, in 1942, to observe the changing ground-water profiles near the banks of Rapid Creek during the passage of a flood-peak, but it is believed that few data were obtained. Small experimental basins of this type are excellent for the study of subsurface-flows because the short duration of overland-flow allows the subsurface-runoff to be separated quite easily.

U. S. Weather Bureau,
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REPORT OF COMMITTEE ON SNOW, 1943-44

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Howard T. Barnes	E. B. Debler	Joseph Kittredge, Jr.	Bestor Robinson
H. K. Barrows	Carl H. Elges	Ray K. Linsley, Jr.	J. H. Ryan (deceased)
Paul L. Bean (deceased)	R. C. Farrow	W. W. McLaughlin	L. K. Sherman
Merrill Bernard	D. B. Freeman	J. D. McVicar	Alden K. Sibley
H. P. Boardman	R. W. Gerdel	James C. Marr	Harlowe M. Stafford
Phil E. Church	Laurence M. Gould	François E. Matthes	Robert G. Stone
George D. Clyde	G. A. Hathaway	Gerard H. Matthes	Walter T. Wilson
E. H. Collins	Eric Hinton	Lacey V. Murrow	R. A. Work

Memories

Memories are much in place if seen against the background of the future. Of many memories, three have grown vivid by recent deaths and represent stepping stones in snow-studies.

ALEXANDER McADIE, when Mount Rose Observatory was in its infancy and the snow-bin and snow-sampler grew up together, came to Reno to lecture in behalf of the infant undertaking.

Now his cheerful valedictory from Hampton, Virginia: "I acknowledge receipt of your card from Tahoe and was delighted to hear from you. Yes, I'd like to be back in California--the chosen land--but old man Time says I am 80 and had better stay put. Not doing much. A little scribbling. Enjoyed your two bits--both in the right key. Keep it up. The war has crowded this place--population about 250,000--twice as much as it ought to be. Heard from FERGUSSON last week. He's still at Blue Hill. Warmest regards as always."

Major EDWARD H. BOWIE, brother of WILLIAM BOWIE, frail, whimsical, but definitely believed that snow-surveying and stream-flow forecasting belonged not with sky-gazing meteorologists but with the water scientists and voted the Western Snow-Conference into the Regional Session of the American Geophysical Union. He never repented.

PAUL L. BEAN, lone snow-surveyor in the Androscoggin of the White Mountains, the basin in which CHARLES E. MIXER, still living, first measured the water-equivalent of the snow-cover in 1901, sturdily without public appreciation conducted snow-measurements weekly on a 300-mile circuit to allot water to the various companies using the stream for power and floating hardwood logs to market. This meant forecasting a year ahead, for hardwood will deteriorate if not promptly marketed.

It was his good fortune to forecast the great flood of 1935 in his basin, where more water than normally passes Niagara poured over the dam at Lewiston. Not a person was lost except by fright. On January 19, he wrote me the following message of vision and enthusiasm: "I have your New Year's Greetings of cheer and hope. I can truthfully say that I never conceived of so many things worth while which needed to be done and never felt more like doing the work." A week later, January 26, he wrote his "Report on snow-conditions in Maine" for the Committee on Snow.

Then on Tuesday, February 8, came the laconic message from MARY C. KEARNS, his Secretary: "This is to advise you, or perhaps you have heard already, that our Mr. BEAN passed away on January 29th from a heart attack. We thought you might be interested in our sad news." His words, written in the fullness of his strength, carry on.

A souvenir that belongs with old memories of snow is the facsimile in Figure 1 of a page from the original notebook of the first snow-tube depths and weighings made in the United States in the winter of 1903-04, about five years before the Mount Rose snow-sampler was built. Dr. HORTON is the honored pioneer.

He writes: "Enclosed is photostat print which I thought might interest you. It is from the original notebook of snow-depth and density-observations, Chancellory Square Park, Utica, New York, by the snow-tube and weighing method, for the winter of 1903-04. The record of December 16 is in my handwriting. The remaining observations were taken by an assistant, WILLIAM NUNN. The last two columns give, respectively, water-equivalent of snow on the ground and the snow-depth ratio, which is the reciprocal of density."

Fig. 1--Reproduction of original record of measurements by Robert E. Horton on December 18, 1903, at Chancellory Square Park, Utica, New York, of snow-depth and density by snow-tube and weighing method

The snow-year, 1943-44

The picture across the Continent is varied, but for water-needs is satisfactory.

Newfoundland (ERIC HINTON)--Grand Lake was mainly ice-free, only some of the coves being frozen over. Consequently, the lake was navigable by tugboat which greatly facilitated obtaining observations of the snow-blanket in that section of the watershed. All the desired areas were visited. As usual, Sandy Lake was frozen over and this section was traversed by dog team. The snow-surface was in excellent condition for this mode of travel and progress was therefore rapid.

The calculated volume of water in the snow-blanket is 48.9 billion cubic feet (BCF), which is 119 per cent of the figure for 1943 and is approximately the average.

Ground-water effect is computed upon the basis of observations at the ground-water wells located in various parts of the watershed. It is noted that ground-water levels were somewhat lower than at the same time last year.

In view of the large discrepancy between the forecast of 1943 and the actual runoff, it is thought prudent to reduce the allowance for "Effective precipitation" during the interval between the snow-survey and the termination of the flood-period. This appears to be quite justifiable for the reason that the ground-water effect, before 1943, was included in the "Estimated effective precipitation" And, while the error in 1943 is almost entirely accounted for by subnormal rainfall during April and May, it is felt that the present adjustment will not be unduly conservative.

Table 1 represents the general accuracy of the forecasts since their inception.

Table 1--Comparison between forecasted and actual flood-runoff at Grand Lake, 1926-1944

Year	Calculated volume water in snow-blanket BCF[a]	Estimated effective precip. March 18-31 BCF	Estimated effective precip. April 1-June 1 BCF	Estimated ground-water effect BCF	Runoff Est. BCF	Runoff Actual BCF	Error BCF	Error Per cent
1926	65.5	....	13.6	....	79.1[b]	90.1	-11.0	12.2
1927	29.3	....	13.6	....	42.9[b]	60.0	-17.1	28.5
1928	39.6	....	13.6	....	53.2[b]	54.4	- 1.2	2.2
1929	46.7	....	13.6	....	60.3[b]	72.6	-12.3	16.9
1930	49.5	....	13.6	....	63.1[b]	64.0	- 0.9	1.4
1931	47.9	....	13.6	....	61.5	63.4	- 1.9	3.0
1932	55.3	....	13.6	....	68.9	71.6	- 2.7	3.9
1933	58.4	....	13.6	....	72.0[b]	84.7	-12.7	15.1
1934	67.9	6.8	13.6	....	88.3[c]	93.4	- 5.1	5.5
1935	55.0	4.4	15.0	....	74.4[c]	70.7	3.7	5.2
1936	49.4	4.4	14.0	....	67.8[c]	91.8	-24.0	26.2
1937	37.7	2.5	15.0	....	55.2[bc]	59.9	- 4.7	7.8
1938	32.5	1.8	15.0	....	49.3[bc]	54.9	- 5.6	10.2
1939	58.4	6.1	15.0	....	79.5[bc]	73.2	6.3	8.6
1940	31.8	3.5	16.0	....	51.3[c]	65.7	-14.4	21.9
1941	48.0	7.0	15.0	....	70.0[c]	73.9	- 3.9	5.3
1942	51.4	6.6	15.0	....	73.0[c]	79.6	- 6.6	8.3
1943	41.1	6.6	15.0	+7.1	69.8[bc]	58.3	11.5	19.7
1944	48.9	3.5	13.6	+6.8	72.8[c]			

[a] Billion cubic feet. [b] Indicates snow-survey incomplete. [c] Indicates estimated runoff to June 15.

New England (PAUL L. BEAN)--I herewith report to you on snow conditions in the Androscoggin Valley, States of Maine and New Hampshire, for the calendar year 1943. Conditions in the rest of Maine are very similar.

The water-year classifies wet, with ample snow last spring and nearly a record snow-cover for the present winter to December 31, 1943. There have been seven distinct high-water periods during the year and the ground-water supply has been heavy throughout the entire year. No severe floods have been experienced along the main river, but one very heavy flood occurred on the storage-area.

The snow-cover in March, 1943, had accumulated to about 24-inches with a water-content of 6.44 inches on the storage-area of 1,095 square miles. Spring rains were about average. The net yield of water from the storage-area from December 1, 1942, to May, 1943, was approximately 100 per cent of the precipitation on the area during that same period. There was a fair snow-cover on the area on December 1, 1942.

For the period June 1 to November 30, 1943, the long-term average yield is a maximum of 54 per cent, a mean of 37 per cent, and a minimum yield of 24 per cent. The percentage for yield for the above period has not been figured, but it will undoubtedly set a new maximum.

Available water is largely obtained from precipitation from November 1 to May 31 of each year, and the snow-survey work is of vital importance to future estimates of water available for power.

Our snow-surveys are being carried on, but not expanded in any degree. Lack of manpower is serious in this area.

The present snow-cover came early this year and on November 22, 1943, there was a snow-cover of 32 inches which, on January 1, 1944, varied from 33 inches to 44 inches with from 6 inches to 7.5 inches of water-content. This snow-cover fell on an unfrozen ground, well saturated. The forest-floor was not frozen on January 1.

This year we are determining daily the British-thermal-unit content of the snow-cover and hope to have a complete record for the winter season.

The year past is notable in this section for the high precipitation and heavy water-yield which has resulted in very large savings in oil and coal in the steam-stations. Lack of manpower has prevented any expansion of our snow-traverses, but we do have plans made for much detailed study of the snow-cover when normal conditions return. In the meantime we are carrying on as best we can.

Michigan (W. U. GARSTKA)--The past winter has been a very open one in Michigan. The deepest accumulation of snow in the winter was that of seven inches in February. I have done practically no snow-surveying this winter because the few snowstorms produced some effects of such shallow depths as to make it impossible to use the snow-tube with any degree of efficiency. There have been many runoffs at our cultivated watersheds, which fact has kept me busy maintaining the station.

I have a completely new crop of student assistants, the training of whom at times becomes a graduate-school job on my part.

Alberta (O. H. HOOVER)--The survey in the vicinity of Lake Louise was conducted on March 27, 28, and 29, 1944.

Snow-depths and water-contents were obtained on eight half-mile courses comprising 125 samples. The mean snow-depth in 1944 for the eight courses was 28.0 inches which compares with 31 inches in 1943 and the mean of 25.7 inches for the previous seven years. The mean water-content in 1944 for the eight courses was 5.7 inches which compared with 6.7 in 1943 and the average of 5.9 inches for the previous seven years.

During the month of March, 1944, the Bow River at Banff was flowing at the rate of 90 per cent of normal. For the next four months, April, May, June, and July in 1944, it is estimated that the Bow River at Banff will discharge 550,000 acre-feet, or about 91 per cent of the long-term normal flow for this period. Again, however, this forecast may be materially disturbed by rains in June and July.

Alberta-Montana (C. S. HEIDEL and O. H. HOOVER)--(International Snow Survey in St. Mary River Basin)--The survey in the Swiftcurrent Creek Basin in Many Glacier National Park, Montana, was conducted on May 4 and 5, 1944. Snow-depths and water-contents were obtained on five courses, comprising a total of 72 samples. The mean snow-depth in 1944 for the five courses was 25.9 inches, which compares with 61.2 inches in 1943 and the median of 50.2 inches for 23 years.

In comparing the data of 1944 with all previous records it is estimated that Swiftcurrent Creek at Many Glacier for the period May to July may discharge 46,600 acre-feet under normal-precipitation conditions, and this runoff represents 70 per cent of the long-term median flow for this period.

Missouri and Arkansas River basins (RALPH L. PARSHALL) --The water-content of the snow-cover on April 1 over the headwaters of the Missouri and Arkansas averages about 80-90 per cent of the nine-year average for this date.

Columbia River Basin and adjacent coastal areas (JAMES C. MARR)--(a) January 1: The winter season is not far enough along, of course, to justify a prediction of what the runoff from the mountain snow-cover will be. However, on account of a much lighter than usual accumulation of snow in the mountains, the water-year may be definitely taking shape.

The snow-cover in all parts of Columbia Basin, and on the west coast generally, ranges from a little more than one-half of the usual amount down to 30 or 40 per cent of the average during past years. Also, owing to the lack of rain last fall, the ground is dry. The amount of valley-precipitation since last October 1 is below normal throughout the Basin. Usually the mountain snow-cover on January 1 amounts to from 25 to 35 per cent of the total winter accumulation. In event the present trend continues and a dry season results, the situation will be alleviated by a relatively large amount of water in storage in reservoirs.

(b) April 1: Unless compensating rainfall occurs during the coming growing season to make up for the indicated deficiency of runoff from snow-cover, approximately 900,000 of the 3,828,000 acres of irrigated land in Columbia Basin will suffer mid-summer and late-season water-shortage amounting to 25 to 30 per cent of the season's supply. Pastures, fruits, and late row-crops will be most seriously affected. A runoff approximating that of 1931--one of the smallest during recent years--and poorly sustained stream-flow in August and September are also in prospect.

These predictions are based on the poor snow-cover on the watersheds and deficiency of soil-moisture in valley-soils. Without exception, the depth of water in the snow-cover in the higher elevations where most of the runoff originates is 50 to 75 per cent below average. The presence in some sections of more snow in the foothills than usual, due to prevalence of below-melting temperatures rather than above-normal precipitation at low elevations, is considered insignificant compared to the deficiency at the higher elevations. Unless spring rain relieves this situation less water can be stored in reservoirs to take care of demands during the late season than otherwise would be the case. Also ground-water supplies generally are less than they have been for the past few years, though apparently they are not as deficient as in 1931.

Owing to the lack of precipitation during the past winter and at the beginning of the growing season, feed on the range is poor and soil-moisture in the dry-farming areas is generally deficient.

British Columbia (S. H. FRAME)--Coastal Area: The coastal precipitation during November to February was 65 per cent of normal. A snow-depth of 7.7 feet and 11.0 feet, respectively, was found on Grouse and Dam mountains adjacent to Vancouver. This is considerably greater than the depth for a number of years previous to 1943.

Okanagan Basin: The depth of water in the snow-pack is 100 per cent of a five-year average. The precipitation from November to February was 76 per cent of normal. The snow-pack was 59 per cent of the precipitation.

Kootenay-Columbia Basin: The average snow-pack was 84 per cent of normal with no apparent loss of water-content. The average temperature at five representative stations adjacent to the snow-courses was 3°F above normal but there was no apparent loss of water-content. The precipitation was 56 per cent of normal. The water-content of the snow on the ground at the end of February was 73 per cent of the precipitation during November to February. The flow of the Kootenay River at Wardner for February was 85 per cent of this month's average for 30 years.

General: Comparing with a period of years previous to 1943 the water in the snow is well up to normal. Precipitation has been less than normal in all areas. In areas where the snowfall was light, and at some of the higher courses, the ground was frozen, otherwise there was no evidence of frost. The above facts should dispel a too pessimistic view of what the summer runoff will be. Snowfall in March and rains in April are yet to come.

Oregon (CHESTER A. CUMMINGS)--Slightly more than 100 snow-courses still comprise the snow-survey network in Oregon, covering the Cascade, Blue, Wallowa, Coast Range, and Siskiyou mountains.

Oregon's prospects of water-supply in late winter of 1944 are deficient in depth and water-content. Unusually light early winter snowfall exposed the watershed-soil to freezing weather which left the ground frozen to a greater than usual depth, particularly in eastern Oregon. This condition may favor relatively greater reservoir-storage from rapid runoff, but is considered unfavorable to sustain runoff for lands depending on unregulated stream-flow. Reservoir-storage on regulated streams insures fair deliveries of water due to a heavy carry-over of water stored in nearly all of the reservoirs from the heavy runoff of 1943.

Colorado River and tributaries in Colorado (RALPH L. PARSHALL)--On the headwaters of these streams the water-content of the snow April 1 averages three-fourths of that one year ago.

For the Colorado, above Grand Junction, the water-content of the snow is only 81 per cent of normal and the runoff of the Colorado at Glenwood Springs during April-July, 1944, is expected to be 1,230,000 acre-feet.

The snow-cover conditions on the San Juan and Dolores river-basins indicate a favorable water-supply for the coming irrigation-season.

The Colorado River Water-Conservation District (F. C. MERRIELL)--Record for the last nine years since snow-surveys started shows that average water-content of snow tends to decrease 2.0-2.5 inches during April, part of which, as well as runoff from current precipitation, usually appears in the rising streams. In 1943, loss of water-content appeared to be over nine inches, but streams did not rise during April. Stream-flow was, however, well sustained all summer, partly from some excess of current precipitation, and from what must have been a very heavy charge of snow-water into the soil, at the time of melting.

In April, 1944, snow-courses gained three inches of water and much unusual snow now (May 12) remains at intermediate levels, but, in spite of rains at low levels, stream-flow barely remained constant. Either now, or shortly after melting starts, the soil should be saturated. On April 1, most western Colorado snow-courses had about 80 per cent of average water-content, with excesses only on Grand Mesa and the San Juan mountains. On May 1, the general excess was five inches of water more than the nine-year average. Snow-density, however, uniformly less than average, showed that the late, loose snow had not and likely would not become compact before melting.

When the last-fallen uncompacted snow has melted, streams will fall rapidly, and it will then depend on current precipitation and the water that has charged the soil, whether or not flow in the late summer is as well sustained as average or even as it was in 1943. It is now believed that in spite of present excess of water-content in snow, late summer flow will be less than in any year since 1940. Total western Colorado runoff may equal the nine-year average, or slightly exceed it.

Utah (GEORGE D. CLYDE)--The Utah Cooperative Snow-Surveys show an unusual distribution of moisture over the State this year. The precipitation has been relatively much heavier in the valleys than on the mountains. The heaviest storms have occurred in the southern part of the State. In general the water-supplies are least favorable in the northern part of the State but get better towards the south and east.

The major storage-reservoirs in Utah have a total capacity of 3,173,000 acre-feet. All of these reservoirs with the exception of Bear Lake, Utah Lake, and the Strawberry Reservoir will fill to capacity this year. Utah Lake and Bear Lake both have more than two years' supply of water in storage. On April 1, 1944, the total amount of water in storage in the major reservoirs was 1,452,000 acre-feet.

In spite of the quite satisfactory outlook for irrigation-water supplies in the State this year, water-conservation should be practiced.

Arizona (RALPH L. PARSHALL)--The present (April 1) water-supply outlook for the Gila, as based on snow-cover, is poor. Practically all snow-courses located on the headwaters of this stream are bare and this stream and tributaries are now much below normal stage. Soil-moisture over the San Carlos Project is deficient but in the lower areas of the valley the soil is in fairly good condition. Unless above-average rainfall occurs during the coming months to augment the irrigation-supplies, it may be expected that the storage in the San Carlos Reservoir will be practically depleted at the close of the season. The present storage in this reservoir is 272,000 acre-feet or just one-half the amount available last year at this time.

On the Salt River and tributaries, at this time there is practically no snow at moderate elevations over their entire drainage-areas. The higher mountain peaks, north slopes, are still covered, south slopes practically bare. The runoff from this high snow will probably add considerably to the present stream-flow. Available storage is now 1,286,000 acre-feet or 85 per cent of the amount held a year ago.

Serious Water Problems for Arizona (ENGINEERING NEWS-RECORD, September 21, 1944)--Indications that large sections of central and southern Arizona soon may be confronted with a serious water-problem as a result of a shortage of precipitation, now in its second year, were contained in a United States Geological Survey report issued September 9 in Tucson. The report, which dealt with ground-water conditions and pumpage, showed that in Pinal County, pumping from underground

supplies has risen from 372,000 acre-feet in 1940 to 515,000 acre-feet in 1943. In other regions, pumpage has increased proportionately. Heavy decreases in water-tables were also recorded in several areas. The report showed that in the Elroy Area the table has dropped 12 feet in the last two years and in the Maircopa District the drop was 10 feet. The total drop in the Elroy Area from 1940 to December, 1943, was 18.5 feet. The Queen Creek Area dropped 2.5 feet in 1942 and three feet in 1943.

Nevada (J. E. CHURCH)--In the Humboldt Basin the snow-cover on March 1 averaged 74 per cent of normal but because the water-table as shown by well-measurements was still somewhat above normal a forecast of 94 per cent probable flow during March to July was issued. Excess precipitation of 249 per cent of normal in June increased the runoff to 120 per cent.

(H. P. BOARDMAN)--The seasonal snow-surveys of April 1 indicate quite consistent results in the different watersheds along the main range of the Sierras, most of the high-altitude surveys being between 60 and 65 per cent of normal while some of the lower-altitude courses were proportionately better. The courses along the Carson Range, which extends northerly and southerly from the east side of Tahoe, also show a higher percentage of normal in water-equivalent than the high-level courses along the main range. The reason for this is that several of our fairly good storms during the past winter came from the east instead of directly in from the ocean and in some cases gave actually more water-equivalent precipitation on this Carson Range than the same storms did on the main range.

California (FRED H. PAGET)--The California snow-surveys indicate that taken as a whole the Sierra snow-pack on April 1 is 75 per cent of normal--three-quarters of an average pack. The distribution is uneven, ranging from 60 to 93 per cent of normal with the greater shortages in the northerly section.

In the Sacramento Valley, with the increased plantings for demands of war, shortages in natural runoff may develop. Economical use will be necessary.

In the San Joaquin Valley, while there will be no water to waste, there should be sufficient to supply all reasonable demands. Present indications are that this year very little water, if any, will flow into Tulare Lake.

The surface of Lake Tahoe should rise about a foot above its elevation on April 1 to 6,227.8 feet. This will be 1.3 feet below the agreed upon maximum allowable elevation of 6,229.1 feet.

Water now being stored back of Shasta Dam (ENGINEERING NEWS-RECORD, January 6, 1944)--Storage in the reservoir back of Shasta Dam began on January 1. From January 1 to April 1 the river-flow at Shasta Dam will be curtailed to an amount less than the usual flow of the river at this point during an average period for January 1 to April 1, but the quantity released will fulfill the estimated requirements.

A Bureau of Reclamation letter addressed to water-users concludes by saying that the storage program at Shasta Dam "is so important to California's contribution to the war-effort that we feel certain it will have your sympathetic and cooperative support."

Southern California (HARLOWE M. STAFFORD)--You may find something of interest in the initial "bulletin" of the United States Geological Survey for southern California. Not much relation to "snow" here.

In developing the estimates of spring and summer stream-flow, it is largely the past behavior of the streams over a long period of years coupled with the common characteristics of the hydrographs, of a more-or-less constant recessional slope, that furnishes the guide. Once the stream-flow for April in the current year is determined, these guiding characteristics and data furnish the means for estimating the amount and monthly distribution of the subsequent runoff in late spring and summer.

It is to be noted that the estimates for those tributaries in the mountain area of the San Bernardino and San Gabriel ranges indicate an expectancy of above-normal summer runoff in the western section, and of normal or slightly less-than-normal runoff in the eastern section.

New snow-courses and cooperation

There is a strong trend toward snow-surveying. The congressional appropriation to the Division of Irrigation of the Soil Conservation Service for determining water-supplies has been greatly increased.

Cooperation of water-users in California with the State Division of Water Resources has become the rule, the former making the snow-surveys and the latter the forecasts.

The city of San Francisco is extending its surveys and the Southern California Edison Company has established snow-surveys even above Florence Lake in "Primitive forest" areas. Five new high-elevation snow-courses now supplement a snow-survey system that serves a watershed, 45 per cent of which is above 10,000 feet.

Eleven new snow-courses have been laid out in the Sacramento, McCloud, and Pit river-areas to provide additional data for forecasting the flow into the new Shasta Reservoir--data vital to the United States Bureau of Reclamation in the operation of the project.

Shelter-cabins for the snow-surveyors in the primitive areas of the National Forests and National Parks are being built in primitive taste to fit their surroundings. At Many Glacier Hotel in Glacier National Park, the "most expensive stream-gage in the world" is a part of the hotel architecture.

In Paradise Valley, Nevada, an effort is being made to combine stream-distribution with stream-gaging, snow-surveying, and observing the weather--a desirable unit where the population is sparse.

In Baker Creek on the Nevada-Utah Line the Nevada National Forest has installed a shelter-cabin to attain the higher snow-courses irrespective of weather and is planning to maintain high-altitude precipitation-gages on Mount Charleston and an additional snow-course on the western slope in connection with the study of artesian water-supplies in Las Vegas and Pahrump valleys. The weather stations are being installed by the United States Weather Bureau.

Meeting war's needs

The real significance of stream-flow forecasting was brought home to the Chairman last spring at the summit of the Sierra Nevada by JACK EDDY, a Division Superintendent of the Pacific Gas and Electric Company that serves northern California. In the Sierra Nevada, snow constitutes 85 per cent of the annual precipitation which is delivered to the streams during April to July. It is therefore essential to use the streams while they flow but collect to full reservoir-capacity for later months. Since the Company's central reservoir, Lake Spaulding, was being emptied faster than it rose, a call had come from tidewater to look at the snow.

To get the widest view of its snow-resources, the Southern California Edison Company has asked for double copies of snow-survey data from the Rocky Mountains westward.

As a means of equalizing snow-water assets, a Power Interchange Committee has been formed as dispatcher of power, to provide the areas possessing least snow. It is a pity that irrigation-water can not be interchanged over long distances to counteract scarcity.

The following classic document by the Pacific Southwest Power Interchange Committee deserves wide publicity:

The importance of precipitation- and runoff-forecasts to the operation of the Pacific Southwest Power Interchange Committee--In order to meet the greatly increased loads resulting from the war, there was formed early in 1942, the Pacific Southwest Power Interchange Committee, which is composed of representatives of the principal electric generating- and distribution-systems in the States of California, Arizona, and Nevada. The purpose of this Committee is to coordinate the generating facilities of the various utility-systems in order to utilize to the fullest extent all available hydro-generated power and to conserve fuel-oil and gas. This Committee has prepared load-resource estimates of the above area for the use of the Office of War Utilities of the War Production Board, and decisions as to the need for additional generating capacity and for the allocation of fuel-oil and gas for the generation of electric energy have been and are being made by the Office of War Utilities on the basis of these forecasts. Reference is made to an article appearing in the December, 1943,

issue of Power Magazine for a more detailed explanation of the function and operation of this Committee.

In view of the critical situation with respect to the supply of fuel-oil and gas in the Pacific Coast Area, it is of prime importance to the Committee to have available at the earliest possible time estimates of the probable precipitation and runoff in the watersheds supplying the hydro-generating plants of the utilities in order to obtain the most efficient integration of hydro- and steam-generating facilities. The Power Interchange Committee has an operating Sub-Committee which makes continuous studies of the load and resources of the various utilities and establishes a general program for the integrated operation of their various generating facilities. This program is revised as often as conditions warrant. It is, therefore, of particular importance that the Committee have available to it at the earliest possible dates any revisions in the estimated precipitation or runoff in the Pacific Coast and Colorado River Basin watersheds. Present indications are that the runoffs in both of these watersheds will be subnormal during the current year which will result in the necessity for substantially increased quantities of fuel-oil and/or gas.

The expediting of the latest data and estimates of precipitation and runoff will greatly facilitate the important work of the Power Interchange Committee in its effort to conserve for military use the vitally essential fuel-oil supply of the Pacific Coast Area.

Snow-conferences

The Western Snow-Conference has kept pace with the Regional Meetings of the Section of Hydrology in the North Pacific Area at Corvallis (Oregon) and the South Pacific Area at Berkeley (California).

The Conference has not only paid up all indebtedness but given quite unsolicited $100 to the Special Fund of the American Geophysical Union in appreciation of the sympathetic and practical assistance rendered by Dr. Fleming for the Union to the Snow-Conferences.

At the request of FRED PAGET, efficient Chairman of the Conference through the war-years, he has been permitted to retire in favor of R. A. WORK of Oregon.

Research

Research has closely followed the pattern of last year but is expanding. The reports are again arranged mainly by regions.

Newfoundland: Soil-Temperature observations (ERIC HINTON)--The soil-temperature observations begun November, 1942 [Trans. 1943, pp. 348-49] were continued throughout 1943 as shown by the accompanying records (Figs. 2-A and 2-B). Unfortunately the clock of the thermograph broke down January 3, 1944, and is still under repairs. Consequently no observations are available from January 3 to date and therefore no attempt can be made to predict the time of flood-commencement.

Maine: (PAUL L. BEAN)--This year we are determining daily the British thermal unit (BTU) content of the snow-cover and hope to have a complete record for the winter season.

Michigan (W. U. GARSTKA)--The hydrology of small watersheds under winter conditions of snow-cover and frozen soil, a project of the Soil Conservation Service at East Lansing, was discussed at the annual meeting of the American Geophysical Union (Trans.,1944, Part VI, pp. 838-874). The project is now completely equipped for detailed observations. The shallow and unstable snow of southern Michigan gives this station special opportunity to study snow and ice in the transitional zone between snow and rain.

(Mr. GARSTKA has resigned to return to college work, but ROBERT G. WHITE, formerly Extension Assistant Agricultural Engineer in Kansas, has been assigned by the Soil Conservation Service to continue the investigations.)

Michigan-Wisconsin (W. U. GARSTKA)--The following report is of special interest since it describes one of the initial practical applications of snow-surveying in the central States, though the Consumers Power Company is reported as having made some surveys in Michigan.

It is interesting to note that the Soil Conservation Service Snow-Study Project, which is located at East Lansing, Michigan, has made its first "field-trial" in Wisconsin.

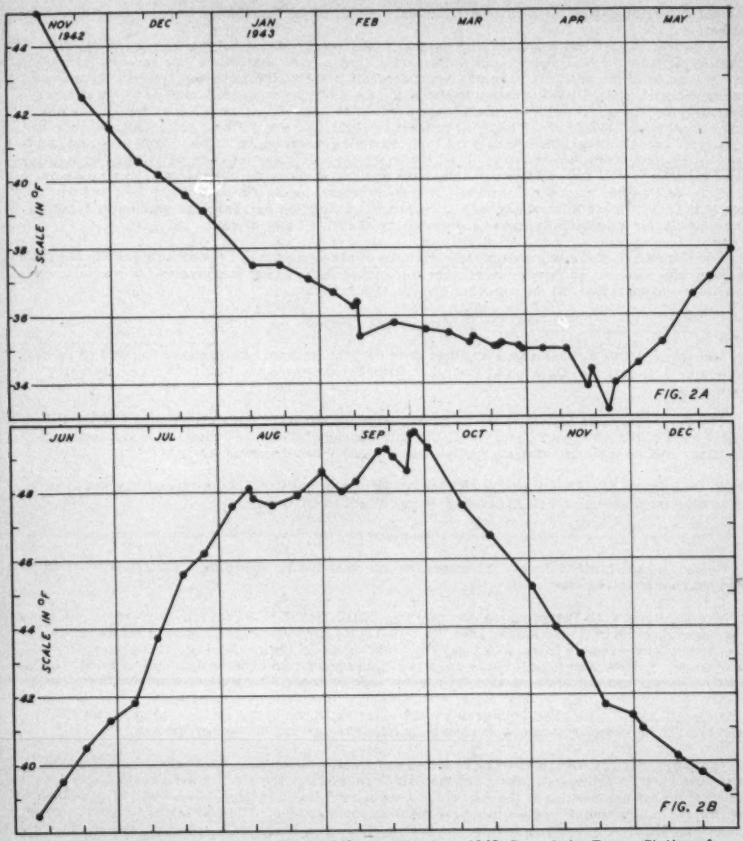

Fig. 2--Soil-temperature, November, 1942, to December, 1943, Deer Lake Power Station of Bowater's Newfoundland Pulp and Paper Mills, Ltd. (Thermometer half mile south of the Forebay with bulb five feet below surface of ground)

Differences in the character of glaciation to which both Michigan and Wisconsin were subjected have resulted in the formation of altogether dissimilar land-drainage patterns in the two States.

Wisconsin has a definite river-pattern in which the tributary streams flow together to form a few large river-systems of which Wisconsin River is an example. Most of the State is in the Mississippi Basin.

A very large proportion of the land-surface of Michigan, which is a part of the St. Lawrence River-System, is occupied by depressions, pot-holes, and swamps. The actual surface-area con-

tributing directly to surface-runoff is considerably less than it appears to be on a map. The rivers do not exhibit the response to heavy precipitation and to snow-melt which one would have reason to expect, taking into account the size of the drainage-basins. Flood-problems are not of major importance in Michigan. Pumping for irrigation is feasible.

The Wisconsin Valley Improvement Company's river-management activities, which are directly concerned with the runoff produced by the melting of snow, offer a unique opportunity to study snow-melt and to make immediate practical use of the information.

Snow-Surveying in Wisconsin (ARNO T. LENZ and MERVILLE W. KYLER)--During the winter of 1940-41, snow-measurements were taken along the first snow-survey course to be established in Wisconsin. These were obtained by the Wisconsin Valley Improvement Company, which operates a series of 21 reservoirs which control the flow of the Wisconsin River. M. W. KYLER, General Manager of the Company, consulted with W. U. GARSTKA, of the Soil Conservation Service in the establishment of the first course, and these two men have been the prime movers in that work in the State. The following winter the course was improved and analytical work commenced to make the records of value to the water-power users along the river.

It is interesting to note that the Improvement Company was organized in 1907 as a result of water-storage projects which date back to 1850. Originally, certain of the water-users built control-dams at the outlets of many of the northern Wisconsin Lakes to hold back spring flood-waters until such time as they were needed to flush logs down to the sawmills along the river. The upper half of the basin was originally densely timbered with many varieties of fine woods, though the majority of the timber was pine. Before the region was penetrated by railroads and log-transportation by rail feasible, the river served as the only highway. Most of the tributary streams were rapid and logs could be driven on them only in times of flood or freshet, which unfortunately would not always coincide with most desirable logging-operations. Hence, the creation of artificial floods from stored water materially assisted the log-drivers.

The Legislature cooperated by making easy the organization of river-improvement companies which were given powers of condemnation for improvement of navigation, and the right to collect tolls for the use of improvements. At this time, water-power was of little importance, and the use of stored water to provide flash-floods was to the advantage of the water-users and their employees who lived in the valley.

However, by the time log-shipment by rail became systematized and economical, the increased use of water-power and the development of the paper-industry required a more even flow of the river. Gradually the various improvement-companies began to store flood-water for use during low-flow periods of the year. In 1904 and 1905, a group of men who were pioneers in the industrial development of the valley, men such as GEORGE A. WHITING of Menasha, WALTER ALEXANDER of Wausau, R. B. TWEEDY of Tomahawk, L. M. ALEXANDER of Port Edwards, Honorable A. H. REID, of Wausau, NEAL BROWN of Wausau, B. R. GOGGINS of Wisconsin Rapids, G. D. JONES of Wausau, I. P. WITTER of Wisconsin Rapids, and W. E. BROWN of Rhinelander, organized a committee to procure the enactment of suitable laws which would enable a single company to perform the "labors and duties of" the several individual companies.

Three things were necessary to success: (1) The supplying of private capital sufficient for the purpose; (2) securing the power of eminent domain so as to enable the establishment of reservoirs wherever proper; (3) the power to enforce contributions to the expense of maintenance and operation and to the payment of an interest-return on the capital invested. Without the last two, the first was impossible. The last two could be secured only by enactment by the Legislature. The efforts of the Committee met with some opposition at first, but this was quickly dispelled when the people of the valley were educated as to the benefits to be derived. The Legislature in 1907 authorized the organization of the Wisconsin Valley Improvement Company as it operates today. Every measure of supervision and control by the State proposed by State officials was accepted by the promoters, and the necessary legislation was enacted by a unanimous vote of the Assembly, and with but few dissents in the Senate.

The reservoir-system, which was then organized, has grown to the point where the storage-capacity today is 17,018,000 cubic feet. The early log-dams have been replaced by permanent structures with adequate control. Financially, the system operates on a non-profit basis, and its charges to the individual power-users are reviewed by the State Public Service Commission annually. It is purely a public-service concern, and does not own any water-power other than one small unit used for operating purposes. Nor does the Company engage in any business other than flow-

regulation and endeavoring to produce, as far as possible, a uniform flow in the Wisconsin River.

It was soon evident in the development of the system that the natural lakes could not be fluctuated sufficiently to be of great help in control of the river-flow. In 1911, Rice Reservoir, Lake Nokomis, was built; it floods 4,200 acres. Since then, Spirit Reservoir (2,200 acres), Willow Reservoir (7,200 acres), Rainbow Reservoir (5,500 acres), and finally, in 1937, the Big Eau Pleine Reservoir (7,200 acres) have been built.

These reservoirs serve 25 power-dams on the Wisconsin River with an aggregate operating head of 628 feet and an installed capacity of 187,000 horse-power. The stored water enables the plants to maintain their natural heads without drawdown, and the efficiency of the plants is increased materially by a higher uniform base-flow. On the other hand, many of these reservoirs are sufficiently close to the operating plants so that considerable water is available on short notice for peak-load demand.

After a few years of operation of the first snow-survey course near Rainbow Reservoir, it became obvious to Mr. KYLER that better knowledge of water-storage in the form of snow and as ground-water would be of much value for operation of the system with greater efficiency. As a result, it was determined to embark upon an extensive hydrologic program of research, which would coordinate to better advantage the work of the agencies now concerned with water-resources in the valley. As a result of conferences with representatives of several agencies, Messrs. KYLER and GARSTKA called a meeting on February 16, 1944, in Wausau, for the purpose of organizing the research-program.

At this meeting and a subsequent one at the University of Wisconsin Hydraulic Laboratory, the Wisconsin Valley Hydrologic Research Project was organized. It operates through a Joint Committee consisting of the Chairmen of the several Sub-Committees, Mr. KYLER and Dr. ARNO T. LENZ, Associate Professor of Civil Engineering of the University of Wisconsin, who represents both the Agricultural and Engineering Experiment Stations of the University. The Sub-Committee Chairmen are: F. C. CHRISTOPHERSON, Stream-flow and Ground-water, representing the United States Geological Survey; W. U. GARSTKA, Snow and Ice Surveys, representing the United States Soil Conservation Service for cryologic research; W. E. HIATT, Precipitation, Evaporation, and Flood Forecasting, representing the United States Weather Bureau; and N. E. MINSHALL, Runoff from Small Areas, representing the United States Soil Conservation Service Research Division. R. S. BROWN, Soil Conservation Service Operations Division, is also a member of the Joint Committee and on several of the Sub-Committees. Colonel L. C. BARNES, District Engineer, St. Paul office, United States Engineer Corps, has offered the assistance of his office in so far as it can help under wartime conditions. Dr. LENZ is Chairman of the Joint Committee.

The Wisconsin Valley Improvement Company will coordinate operations problems in the area. The University of Wisconsin Experiment Stations will coordinate analysis of the data obtained. Anticipating postwar expansion of educational programs, it is hoped that many fine hydrologic-thesis programs on the graduate level will become available from the data collected now.

The program for expansion of the snow-survey includes the establishment of three new snow-courses as follows: Burnt Rollways, which will give an index of water available to three reservoirs; Willow, three reservoirs; and Big Eau Pleine, which will be an index to the drainage-area (365 square miles), tributary to the reservoir of the same name. Together with Rainbow, which indexes five reservoirs, these courses are representative of 80 per cent of the storage-capacity of the system.

Equipment is being installed at the Rainbow Reservoir Meteorologic Station for the measurement of soil-moisture content under the snow-cover. The methods to be followed will be the same as those used by Mr. GARSTKA at the Michigan Hydrologic Research Project at East Lansing.

These projects are those of the Sub-Committee on Snow and Ice; the other Sub-Committees have plans under way for similar expansion.

Continental Divide (ROCKY MOUNTAIN FOREST AND RANGE EXPERIMENT STATION 1943, by C. A. CONNAUGHTON, DIRECTOR)--In our annual report for 1943 we have summarized results of several years of work on the relation of forests and snow in the high Rockies. I am sure you will find this material to be of interest.

Forests and snow: Highlights 1943

In a commercially clear-cut lodgepole pine stand 31 per cent more water was available for stream-flow than in the virgin forest. Of a total annual precipitation of 24.5 inches, 10.63 inches of water were available for stream-flow in the virgin forest and 13.88 inches in the commercially clear-cut area.

Winter storage of snow in a lodgepole-pine forest increased in proportion to the intensity of timber-cutting. Three seasons of measurement have established that an average of 7.60 inches of water accumulated in the snow on uncut plots before melting began, while 9.59 inches--an increase of 26 per cent--was found on "commercially clear-cut" plots, from which all trees larger than 9.5 inches in diameter had been removed.

Timber-stand improvement, which removed cull trees from the reserve stand after commercial cutting was completed, resulted in an additional increase of five per cent of water stored in the winter's accumulation of snow.

The degree of timber-removal caused no appreciable change in the date on which ground became bare in the forest. However, as more snow was present on the cut-over plots, the rate of melting was necessarily more rapid as it required no longer to disappear than the smaller amount in the uncut stand.

Spring and summer precipitation reaching the ground beneath the forest-canopy was decidedly increased following cutting. In the heavily cut-over area an average of 3.02 inches or 33 per cent more spring and summer precipitation reached the forest-floor annually than in the uncut stand.

Autumn moisture-deficits in forest-soil, caused by transpiration and evaporation during the summer, are decreased by timber-cutting if summer rainfall is normal and well distributed throughout the season. If rainfall is low, especially toward the end of the summer, deficits are large but show a smaller response to timber-cutting.

Total water-losses from the soil were generally constant in the lodgepole-pine type for varying intensities of timber-cutting because of the balancing effect of evaporation and transpiration.

Almost three-quarters of the stream-flow from forested watersheds in the high Rocky Mountains is derived directly from snow-runoff. Of the average annual discharge received from a controlled watershed, about 70 per cent flows directly from melting snow, five per cent from summer rains, and the remainder as perennial base-flow derived from ground-water which was probably supplied mainly from snow-melt.

The rise in spring stream-flow usually lags two weeks behind the beginning of snow-melt, indicating the period required to satisfy soil-moisture deficiencies carried over the winter from the preceding growing season.

From the standpoint of watershed-management, a stand of aspen is a very favorable forest-cover. Greater quantities of snow are stored in aspen than in second-growth lodgepole pine or open fields. The deficiency in a stand of pine is caused by interception and in the open fields by wind-movement and evaporation.

In a pure and normally stocked stand of aspen with leaves fully developed, interception of summer rainfall was 0.4 inch less than in an adjacent fully-stocked stand of second-growth lodgepole pine.

Influence of timber-cutting on water available for stream-flow from a mature lodgepole-pine forest: Experiments

The problems studied were initial snow-storage, duration of snow-melt, evaporation from stored snow, net precipitation reaching the ground, autumn soil-moisture deficiencies, effects of timber-cutting on the soil, comparison of results with those at Wagon Wheel Gap, Colorado.

Other experiments were the effect of various types of forest-cover on stream-flow, aspen versus pine as watershed-cover, influence of thinning dense young lodgepole pine on factors affecting water-yield, influence of a mature spruce-fir forest on watershed factors.

Results from the thinning experiments are wanted as soon as possible, because the thinning of dense stands of young lodgepole-pine for watershed-improvement can provide a large reservoir of constructive and profitable work during the postwar period. Before we can enter into such work on a substantial scale, however, we must know how to do the job in the best and safest manner.

The comparison of results with those at Wagon Wheel Gap will be presented under "Themes of leading interest" toward the close of the Report (p. 799).

Because of the relative scarcity of measurements of evaporation of snow, the following brief paragraph by Director CONNAUGHTON is added as a datum in the study of the disappearance of snow.

Evaporation from stored snow--As indicated in the study of water-losses, we could obtain records of snow-evaporation only by means of a large stationary pan, located in a forest opening in the general vicinity of these plots. For four years (1940-1943), this pan lost an average of 2.23 inches of water by evaporation for the whole winter and the spring melting-period. Since snow-evaporation might be expected to vary with intensity of timber-cutting, estimates of this factor were included in our plot-results. Starting with 0.80 inch per year on the uncut areas and rising in linear relation to intensity of cutting, these estimates reached a maximum value of 2.00 inches on the commercially clear-cut areas. Such a large variation among the timber-cutting treatments may exceed the real variation; but at least it keeps our results on the conservative side in appraising the aggregate influence of cutting on water available for stream-flow.

Fuller details of evaporation-measurements from pans of various sizes given in his 1942 report [Trans. Amer. Geophys. Union, p. 354, 1943] indicate that the observed data from the large pan (500 square feet) are considerably higher than the results obtained with small weighing-pans.

Summer rains and stream-flow

The conviction that summer rains east of the Continental Divide, despite their preponderance over winter precipitation, have only minor influence on the runoff is borne out by CONNAUGHTON'S conclusion that "of the total annual discharge, about 70 per cent flows directly from melting snow and precipitation added during the snow-melt period; less than five per cent from summer rains; and the remainder consists of stable, perennial base-flow which is doubtless derived largely from snow-melt during the current and preceding years.

Since this estimate applies to forests that are probably at higher altitudes, one wonders whether the rainfall at the lower altitudes has a greater influence on summer flow. A study of rainfall and altitude similar to that in the Ruby Mountains, Nevada, could easily be maintained along the highways to the summit of Pike's Peak or Mount Evans or on the highway over the divide from Estes Park to Grand Lake.

Western Colorado: Snow-density (F. C. MERRIELL)--The February Snow-Bulletin issued for Nevada is interesting and should be compared with our regular forecast. Seemingly both areas are not up to par this year. The things that strike me about the records it gives is the higher density it shows. You will note that this year some of our areas have much lower than usual density, but our densities are always less than the ones from Nevada.

As experience grows in this matter I am more impressed with the possibility that in some attention to density we may have help. There are as we all know many factors connected in some way with weather, most of which would still be imponderable if we had sufficient high-altitude weather stations. You will have noted in the last Transactions [pp. 351-352, 1943], the short paper on the Fraser Experimental Forest and the use there made of soil-surveys in the fall. That is coming, perhaps, in all our work.

The two charts sent you [Trans. 1943, pp. 356-357] were only a starter. If we ever have the time, we will start plotting the individual stations with time of year and density as arguments, which, taken with the local conditions and such data on weather as we can get together to qualify the showings thus obtained, will help us determine if any help is forthcoming from the matter of density.

Certainly density will increase with age, even if there is no great increase in snow depth, but it seems worth a trial to find out if by a closer study of density we may not have some useful answers.

Sierra Nevada: Progress-report, Soda Springs Cooperative Snow-Research Project (R. W. GERDEL)--Rapid development of the agricultural and industrial economy of the West has resulted in increasing demands on the natural-water reservoir represented by the mountain snow-packs. Economic use of the spring and early-summer runoff from melting snows depends upon a satisfactory qualitative and quantitative evaluation of the snow-fields at the higher elevations.

The Nevada Agricultural Experiment Station and the United States Weather Bureau have maintained a Cooperative Snow-Research Laboratory at Soda Springs, California, near Donner Summit in the Central Sierra, for the past two seasons. One of the projects at this laboratory has been the study of performance of various types of precipitation-gages and the development of recommendations for the improvement in design of both seasonal and recording snow-storage precipitation-gages.

Description of gages and installations at Soda Springs--During the season of 1943-44, 13 precipitation-gages were under observation at the Soda Springs Cooperative Snow-Research Project. Three of these gages were of the recording type and ten were non-recording storage-cans varying in capacity between 24 and 190 inches of precipitation. Several of the gages were equipped with shields of the Alter type. Some differences in design, construction, and method of installation permitted studies on necessary improvements in these shields.

Eleven gages were charged with a calcium-chloride solution (34 per cent), which functioned as an anti-freeze and liquefying agent. One gage received an initial charge of ethylene glycol (commercial Prestone) but later was recharged with calcium chloride.

A small amount of automobile oil served as an anti-evaporant. One gage received no anti-freeze. This gage was serviced by the regular Weather Bureau Cooperative Observer who measured the precipitation by melting the accumulated snow and discarding it each day.

The gages were installed at two locations near the headquarters buildings. One location consisted of an elevated platform about 200 feet to the rear and south of the Soda Springs Hotel. The other location was a pasture about 1,000 feet southeast of the hotel. The platform at the rear of the hotel was of tight board construction and the accumulation of snow occasionally interfered with satisfactory operation of the gages. The platform in the pasture was of more open construction which resulted in lesser accumulation of snow. Gages on individual towers were free of any accumulation. A detailed description of each of the gages listed in Table 2 follows:

Gage 1: An 8-inch by 24-inch copper can, standard Weather Bureau gage of the climatological network. Located on platform near hotel. Not provided with wind-shield. No anti-freeze used. Serviced each day.

Gage 3: A special conical gage designed and constructed by the United States Engineer Department, with 8-inch orifice and 190-inch capacity. A moving collar set in gimbals was provided to permit the loosening of adhering snow by the action of wind on the collar. Provided with a reinforced Alter shield. Charged with 90.5 inches of calcium-chloride solution (34 per cent) at the start of the snow-season. Located on platform near hotel.

Gage 4: A galvanized iron 8-inch by 24-inch can provided with a standard Alter shield and charged with approximately six inches of calcium-chloride solution (34 per cent). Recharged as needed. Located on platform near hotel.

Gage 5: Standard Friez reconnaissance (recording-type) gage of the Weather Bureau Hydroclimatic Network mounted on a 20-foot steel tower at rear of hotel and adjacent to the platform on which the other gages were installed. Standard Alter shield. Four-day chart, spring clock, eight-inch orifice discharging into bucket with 12-inch capacity. Charged with approximately six inches of calcium-chloride. Recharged as needed.

Gage 6: Same as Gage 4 except located on platform in pasture.

Gage 7: Stevens "Q", 30-day recording gage. Eight-inch orifice on a 30-inch open tube discharging into large bucket of approximately 18-inch capacity. Provided with reinforced Alter shield. Charged with calcium-chloride solution (34 per cent) and recharged as needed. Located on platform in the pasture.

Gage 8: An 8-inch by 24-inch copper can without Alter shield. Charged with approximately six inches of calcium-chloride solution (34 per cent) and recharged as needed. Located on platform in the pasture.

Gages 9 and 10: Cylindrical eight-inch containers, 36 inches deep, mounted on individual ten-foot towers in the pasture and equipped with standard Alter shield. Charged with approximately ten inches of calcium-chloride solution (34 per cent).

Table 2--Comparison of seasonal catch by different types of precipitation-gages and snow-course

Gage No.	Description	Catch Jan. 1, 1943 to March 6, 1944	Deviation in per cent from mean of				
			All gages	Shielded gages	24-inch standard 8-inch capacity gages	Large-capacity gages	Unshielded gages
1	Unshielded, 8-inch standard gage read daily	30.04	-15	-17	- 3	-22	+ 9
3 [a]	Shielded storage gage, 190-inch capacity	27.40 [b]	+16	+13	+32	+ 7	+49
4	Shielded, 8-inch standard gage used as storage-gage	23.35	- 1	- 4	+13	- 9	+27
5	Shielded Friez reconnaissance-recorder	23.35	- 1	- 4	+13	- 9	+27
6	Shielded, 8-inch standard gage used as storage-gage	20.22	-14	-17	- 2	-21	+10
7	Shielded, Stevens Type Q recorder	25.70	+ 9	+ 6	+24	0	+40
8	Unshielded, 8-inch standard gage used as storage-gage	16.70	-29	-31	-19	-35	- 9
9	Shielded, 8-inch by 36-inch gage used as storage-gage	24.79	+ 5	+ 2	+20	- 4	+35
10	Same as 9	24.95	+ 6	+ 3	+20	- 3	+36
	Snow-survey course	29.9	+27	+24	+44	+16	+63
	Means						
	All gages and snow-course	23.84	...	...	...	...	...
	All shielded gages (3,4,5,6, 7,9,10)	24.27	...	...	...	...	...
	All 24-inch capacity gages (1,4,6,8)	20.73	...	...	...	...	...
	All large-capacity gages (3,7,9,10)	25.71	...	...	...	...	...
	All unshielded gages (1,8)	18.37	...	...	...	...	...
	Deviation of all gages in per cent	....	12	12	19	13	30
	Deviation at all gages within classes	....	...	7	10	4	9

[a] Designed by United States Engineer Office, Sacramento, California. [b] Stick-measurement.

Table 2 summarizes the results of the season's snow-observations. As has been noted, a number of the snow-gages were placed on the platforms used to service the recording gages. This resulted in some crowding which is believed to detract from the value of the data for comparative purposes.

Observations during specific storm-periods indicated that the unoccupied volume of the precipitation-gage might directly influence the catch of subsequent snow. This appeared to be particularly true of all cylindrical gages. In order to test the theory derived from these observations, the precipitation-measurements from all cylindrical gages for the storm-period which produced ume previous to the storm. Since Gage 7 (Stevens "Q") had, because of its construction, a relatively constant free-board of 30 inches, the residual volume of the individual gages was compared with their precipitation-catch expressed as a percentage of the catch by Gage 7. The resultant analysis is presented in Table 3, showing a correlation between residual volume and amount of precipitation caught.

Melting of the snow may be prevented at low temperatures by the formation of a relatively viscous oil-film over the liquefying agent. Such films help to support a snow-column above the liquefying agent. A cylinder of snow may freeze to the walls of a cylindrical gage and vertical contraction of the snow-column may then actually lift it away from the anti-freeze solution. This phenomenon has been noted on many charts from recording gages throughout the West. Under such

Table 3--Relationship between residual volume of storage-gages and precipitation-catch, Soda Springs, California

Residual volume in inches depth prior to snowfall	8.8	11.1	11.1	11.7	12.4	13.2	13.9	14.2	14.7	15.6	22.9	23.2	27.0	27.2
Precipitation-catch expressed as per cent of catch by Gage 7	14	41	85	35	35	30	50	45	40	43	72	68	72	70

Actual catch by Gage 7: February 23 to March 1, 5.10 in; March 2-6, 3.75 in.

(Periods characterized by high winds, low temperatures, powdery snow with little adherence to or capping of gages)

conditions, the charts show a rapid decrease in recorded precipitation, followed, as temperatures increase, by a sudden increase in recorded precipitation as the slug is released and falls into the gage-bucket.

Observations during several storm-periods indicated that the conical gage, designed by the United States Engineer Department appeared to be functioning more satisfactorily than any other gage under observation. During the worst wet-snow storm-period of the past season the orifice was never completely closed. The large initial volume of calcium-chloride used in this gage appeared to maintain a low freezing-point throughout the winter with resultant greater melting efficiency. The conical design prevented the development of a core of snow and reduced adherence to the internal walls of the gage. The greater area of exposed anti-freeze and oil-film compared to the area of the collecting collar permitted the snow to displace the oil-film and attain contact with the anti-freeze. The only objection to this type of gage is the inability to determine period-precipitation by weighing or directly by depth-measurements. Period-precipitation must be interpolated from depth-measurements by use of a table or graph of corrections. Seasonal precipitation can be determined by draining and weighing the total contents.

Miscellaneous studies and observations--The possibility that a gage provided with a plastic orifice might have less difficulty with adhering wet snow because of the lower thermal conductivity of the plastic was investigated. A standard eight-inch can was provided with a collar of cellulose nitrate three inches high but failed to produce the results desired. Adherence of snow was increased rather than decreased. It is probable that the transparent plastic absorbs very little radiation and being a poor conductor, little of the solar heat absorbed by the black metal can is transmitted through the plastic to the snow.

Observations indicate that the thermal coefficients of the various metals and other materials from which gages might be made are probably of little importance since the amount of material from which the gage is constructed is small in proportion to the liquid contents. It is believed that a dark-colored, flat-finished exterior surface on a gage would be very effective in absorbing solar radiation with resultant rapid melting of snow-caps or ice and snow within the gages.

Internal surfaces of the gages should be well covered with a chemical resistant paint to reduce the electrolytic action of the calcium-chloride solution.

Prestone was tried as a liquefying agent in one gage and proved to be as effective as calcium-chloride until diluted by an equal volume of precipitation, after which the freezing-point rises rapidly. It is much more expensive than calcium-chloride and has the disadvantage that the liquid content of the gage cannot be as readily reduced to a low freezing-point by subsequent additions of ethylene glycol as by the addition of calcium-chloride salt.

Among the recording gages, No. 7 (Stevens "Q"), produced satisfactory results during the past season as a long-period recorder, which for use in remote locations is an advantage over the Friez type. It is believed that this gage can be further improved by modifying the collecting and discharge cylinder to a slight conical shape. This should prevent internal adhesion of snow which occurred at times.

Summary--The results of observations and studies of precipitation-gages during the snow-season of 1943-44 at the Soda Springs Cooperative Snow-Research Laboratory indicate that seasonal snow-storage precipitation-gages should have sufficient volume for quantities of 34-percentage calcium-chloride solution at least equivalent to the expected seasonal precipitation. Where minimum temperatures below +15°F may be expected in the late winter, the quantity of anti-freeze should be increased to one and one-half or two times the expected seasonal precipitation. The gage should be sufficiently large to hold the selected quantity of anti-freeze solution plus the expected seasonal precipitation with a residual depth of approximately 24 inches.

The storage-portion of the gage should have a larger diameter than the collecting collar in order to expedite liquefaction of the falling snow.

All gages should be painted a flat black on the outside to increase the absorption of solar heat and thereby increase the rate of snow-melt within the gage and reduce the cohesion of snow to the minimum.

Based upon the experience obtained with various snow-storage precipitation-gages in the snow-fields of the high Sierra during the snow-season of 1943-44, the Weather Bureau is proceeding with the design and construction of improved models for trial during the snow-season of 1944-45.

Optimum environment of the red-fir forest of the Sierra Nevada--By the aid of snow-survey data H. J. OOSTING and W. D. BILLINGS have determined the following optimum environment, as a detail of a larger study of the ecology of the red-fir forest of the Sierra Nevada [Ecological Monogr. No. 13, July, 1943]:

Since most of the precipitation occurs during the winter months it is not surprising to find that, at the higher elevations, most of the moisture falls in the form of snow. Heavy snowfalls are a characteristic feature of the high Sierra Nevada. A maximum depth of 60 inches in one day has been recorded at Giant Forest, Tulare County, California. At Tamarack, Alpine County, California, the average seasonal snowfall is 449 inches while the maximum recorded for the same station is 884 inches, or more than 73 feet, during the winter of 1906-07.

The red-fir community reaches its best development in approximately the same altitudinal zone that snowfall reaches its greatest depths. This, however, is not the zone of maximum total precipitation. The greatest precipitation (actual and potential) occurs lower down the western slope where pressure, temperature, and moisture-content of the air are all most favorable for maximum precipitation. The zone of greatest precipitation thus coincides with the luxuriant mixed coniferous montane forest between elevations 5,000 and 7,000 feet and is of primary importance in its expression.

The deep winter snow-pack is a constant characteristic of the fir community and supplies on melting about 80 per cent or more of its effective water. The snow-pack is more than just a water-supply. It provides insulation and protection from the cold dry winter winds and thus protects the woody reproduction until it is firmly established. Much reproduction never exceeds the height of the pack, for unless the terminal shoot can grow vigorously in a single season from below the pack to a height of a foot above the pack, it may never reach that height. Snow-blast and low temperature within the first few inches above the glazed surface of the snow would, in many cases, kill back the terminal shoots of saplings already weakened by the intense competition for light and water. The great abundance of woody vegetation below two meters in height seems to be greatly influenced by and possibly caused by the presence of the snow-pack.

The last of the snow-pack has usually melted by mid-July, although in some places it may have disappeared by late June. Frosts may be expected until late June or even into July and usually appear again by the middle of August. The growing season as ordinarily considered is thus very short, varying from about 40 to 70 days throughout the type. This seems too short for luxuriant forest-vegetation, and probably is, for it really indicates the growing season for cultivated crops and not for the native vegetation. Most of the herbaceous plants are perennials and begin growth very early, probably before all the snow has melted and certainly before the last frost. Many of these plants seem able to withstand very low temperatures both at the beginning and the end of the normal growing season without any apparent ill-effects. It is also probable that the frosts may not be as severe under the forest-cover as in the open where observations were made.

The temperature is low in the winter but not excessively low. The thick mantle of snow must provide excellent insulation and it is improbable that soil-temperatures ever go below 0°F. The

summer temperatures are cool. Even during the growing season, it is probable that night minima are always below 50°F.

The climate of the red-fir zone can be summarized as cool, with clearly defined winter-wet and summer-dry seasons, the precipitation being mainly in the form of heavy snowfall. Late and early frosts in combination with the deep snow-pack cause the growing season to be short and coincident with the driest portion of the year.

Snowflake oddities--(BULLETIN AMERICAN METEOROLOGICAL SOCIETY, OCTOBER, 1943)--GAYLORD PARKS, in a letter to the Editor of The Boston Herald says: "While I was walking down Newbury Street this afternoon, something white the size of a piece of blotting paper hit me in the face with such force that I sat down on the sidewalk. It was a snowflake. You may tell your readers that a man in Boston was bowled over by a single snowflake on April 14. Will winter never end?"

Fitchburg, Massachusetts, January 12--"This city experienced a snowball snowfall today. The balls, porous and in some cases more than two inches in diameter, floated to the ground so gently that a few of them remained unbroken. When told of the phenomenon, Dr. CHARLES F. BROOKS, Director of Harvard University's Blue Hill Observatory at Milton, said that although it was rare, he had seen similar ball-like flakes fall in Worcester some 15 years ago. Dr. BROOKS said the phenomenon was possible only when the original snowflakes are large and have enough points to contact each other easily as they drift earthward, and only when the temperature is near freezing."

Snow-cover and fish-life

JAMES V. LLOYD, Superintendent of Lassen Volcanic National Park, says in his letter of June 14, 1944, to the Chairman: "Reference is made to the excellent and interesting Report of the Committee on Snow, 1942-43, recently received in this office. It is noted on page 361 that a 'rare illustration of the survival of fish under snow is the school of large trout alert but contented in Lake Helen (8,400 feet) in Lassen National Park where in April, 1941, the snow-cover was 24 feet deep with a normal depth of at least 16 feet.' To our knowledge fish have never been found in Lake Helen, and a survey of some park waters made in 1942 by JAMES W. MOFFETT of the Fish and Wildlife Service, indicated that the lake is 'practically barren of plant-life, plankton is also very scarce, and there may be dissolved slats or other chemical substances in the water which poison the fish, but this seems unlikely because trout are able to survive in Emerald Lake which is nearby and probably receives water by seepage from Lake Helen.' We believe the writers of the report may have confused the two lakes mentioned above. There are many large trout in Emerald Lake, which is about one-half mile southwest of Lake Helen, at a slightly lower elevation.

"The park staff was particularly interested in the section of the report (p. 372) dealing with the locations of the greatest snow-depths."

J. E. CHURCH comments in his reply to Mr. LLOYD as follows: "We are under deep obligation to you for correcting our note in the Report of the Committee on Snow for 1942-43 regarding the presence of fish in Lake Helen. The observation was my own but plainly I confused Lake Helen and Emerald Lake, the former of which I evidently did not see at all in traversing the road around the mountain. The presence of the snow-survey cabin nearby this lake, which is associated with Lake Helen Snow-Survey caused me to misname the lake. The fact, however, is the important thing that trout may survive under great depths of snow. Has a survey been made of plant and chemical conditions in Emerald Lake to see whether there is any variation between Emerald Lake and Lake Helen? Even Emerald Lake did not seem to have much plant-life. The Park staff should continue holding the banner for greatest snow depths until greater depths are actually found elsewhere. Mount Rainier seems to be your chief contender for honors."

In reply Mr. LLOYD wrote: "Reference is made to your letter of June 27, in which you ask whether or not a survey has been made of Emerald Lake to determine plant and chemical conditions. No such survey has been made, so far as is known. Mr. MOFFETT did not make a study of Emerald at the time he reported on Lake Helen. It is evident that there must be some difference in the chemical conditions of the two lakes, however, since fish survive in Emerald but not in Lake Helen. When trout were planted in the latter, they were dead within a few days and washed up on the shore. Your assumption that there is little plant-life in Emerald Lake is correct. All that has been observed is a little grass along the west shore in the shallows.

"We were glad to learn that our pride in Lassen's snow depths is justified."

Instrumental equipment

Pack bags--The Nevada carrying case developed by PHILIP COWGILL and CARL ELGES has been described in the Transactions [p. 148, 1941) and the Oregon pack-frame and attached case developed by R. A. WORK appears below. Both are products of snow-surveying and have been presented at Snow-Conferences.

Figures 3-A, 3-B, and 3-C illustrate the latter. The chief feature of the case is its loose attachment to the pack-frame so that in the event of a forward fall the heavy load will be thrown loose and thus free the falling skier from its momentum. In summer the pack-frame can be used in carrying supplies. Mr. COWGILL feels that at least a belt should be drawn tightly around the case to reduce looseness and swaying.

Fig. 3--Oregon pack-frame and case by R. A. Work (courtesy Ernie Mack): (A) Rear view of double case; (B) front view of pack-frame and straps; (C) side view showing attachment of carrying case and frame (hooks are open to expedite detachment when pack is turned upside down in falling)

Plastics--The study of plastics in connection with the improvement of precipitation-gages and snow-samplers is still continuing. Transparent plastic material for the orifice of precipitation-gages has been found to cause adhesion of moist snow rather than retard it, and to have little radiation-effect in melting the snow-column in the throat of the gage after the Sun returns. Heavier opaque plastic will now be tested.

Thinner plastic tubes for a snow-sampler must be sought. The walls of most of the available plastic tubes are too thick for the attachment of the present Mount Rose cutter.

The Los Angeles Department of Water and Power that requires long samplers for the deep snow of the High Sierra writes through GEORGE A. LEWIS that "we will still use the original steel tubes since they fulfill our requirements exactly."

Water-proof field note-books for snow-surveying--Field note-books have long been chemically treated to make the sheets waterproof irrespective of weather or water. While waterproofing did

not impair the legibility of pencilled entries, it prevented ready adhesion of ink in the copies made of the record, unless an untreated set of record-sheets was kept especially for such use. The California Cooperative Snow-Surveys has now procured a waterproof paper equally good for pencil or pen.

Strength of primary cells at various solution-temperatures--The success of primary cells in an insulated case, mainly buried in snow at the Soda Springs Snow-Study Project has prompted the desire to continue the test without insulation. As a basis for such test E. W. NEWCOMB of the Primary Battery Division of Thomas A. Edison, Inc., San Francisco, has obtained from its Engineering Department Tables 4 and 5 relative to the low-temperature characteristics of Edison primary cells. Mr. NEWCOMB states that primary cells have long been employed by the Southern Pacific Company along its route through the Great Basin where winter temperatures are particularly low. These, however, appear to receive partial insulation in chambers in the ground. Insulation in mountain rocks, where batteries might be employed, would be slight.

Table 4--Maximum amperes continuous discharge per cell at various constant-solution temperatures to full rated capacity

Type Edison cell	A. H. cap. to 0.5 V per cell	No. of plates	Temperature in °F								
			0°	10°	20°	25°	30°	40°	50°	60°	70-90°
HA-252	250	9	1.6	2.4	3.3	3.8	4.4	5.6	7.0	7.8	9.00
S-500	500	3	...	...	...	0.6	0.7	0.8	1.1	1.3	1.75
M-500	500	5	...	...	...	0.8	0.9	1.2	1.5	1.9	2.25
HA-500	500	9	...	...	...	2.0	2.4	3.4	4.5	5.5	6.50
HA-902	500	9	2.0	3.0	4.2	5.0	5.6	7.0	8.5	10.0	12.0
M-1000	1000	5	...	...	...	1.0	1.2	1.8	2.2	2.8	3.50
HA-1000	1000	11	...	...	...	2.5	3.2	5.2	7.0	7.8	9.00
HA-1302	1000	13	1.5	3.5	5.5	6.5	7.6	9.8	12.0	16.0	20.00

Table 5--Maximum amperes intermittent discharge per cell at various constant-solution temperatures to full rated capacity

Type Edison cell	A. H. cap. to 0.5 V per cell	No. of plates	Temperature in °F								
			0°	10°	20°	25°	30°	40°	50°	60°	70-90°
HA-252	250	9	2.1	3.2	4.3	5.0	5.7	7.3	9.00	9.7	10.4
S-500	500	3	...	...	...	1.0	1.1	1.4	1.75	2.0	2.2
M-500	500	5	...	...	...	1.3	1.4	1.7	2.00	2.2	2.6
HA-500	500	9	...	...	...	3.6	4.0	5.0	6.00	6.7	7.5
HA-900	500	9	2.6	3.9	4.9	6.4	7.0	8.1	10.5	12.2	13.5
M-1000	1000	5	...	...	...	2.5	2.7	3.1	3.70	4.0	4.5
HA-1000	1000	11	...	...	...	4.5	5.4	7.0	8.70	9.5	10.4
HA-1302	1000	13	2.0	4.4	5.8	8.0	9.2	12.0	14.50	19.2	22.0

The Polar Regions

Although secrecy still veils the intense activity in the Arctic, a few releases have been made that indicate the character of work being done. These have been augmented by narratives of earlier exploits and experiences. Next year a wealth of material should be released.

Of a lighter nature are two articles in the Geographical Magazine of London [April, 1943], "In Greenland's flowery valleys" by ISOBEL W. HUTCHISON, and "Antarctica I: The last continent" by F. D. OMMANNEY [December, 1942]. A third article appears in The Polar Record [July, 1943] on "Arctic travel and warfare in the Sixteenth Century" by the Rev. M. P. CHARLESWORTH.

Human adjustment to polar environment is represented as follows: "The study of man's reaction to a polar climate", by BRIAN ROBERTS; "Snow caves", by ROBERT MOSS; and "Light transmission through snow", by L. C. PORTER [all in Polar Rec., July, 1943]. Caves melted more slowly "if the roof were rounded into a 'Norman arch', which would allow any melt-water or condensation to work its way in a thin film away from the crown of the arch and trickle slowly down the walls, care being taken to leave no pockets where warm air could collect" or points from which melt-water could drip. Under light fluffy snow at +10°C, it was found that the light-transmission at 5/8-inch depth was 6.3 per cent and at 3-1/4-inch depth only 0.8 per cent of that at the upper surface.

The light in a snow cave of six-inch thickness would obviously be dim irrespective of the density of the snow.

Arctic engineering is visualized in the following excerpts from "The saga of the Greenland Bases" [Eng. News Rec., September 7, 1944]: "In Greenland it was as cold as 60°F below zero, the wind had a velocity as high as 160 mph, the fjords sometimes were full of ice all summer so equipment could not be landed and 'permafrost' had to have careful consideration in preparing sub-bases for runways and foundations for buildings. Fill-material and drainage-structures for runways were placed in the coldest weather but during the winter months work was concentrated on buildings to leave the three or four summer months for runway-construction, particularly the surfacing.

"All materials for construction and for living in Greenland, except sand-and-gravel aggregates, were shipped from the United States. No trees grow in the regions where the bases have been constructed and air-command flyers even took spruces in from other points for the workmen to have Christmas trees. All food, except a few fish caught for recreation, was taken in.

"The secret of working in extreme cold, according to Colonel RATHJENS, is always to keep dry. Clothing should be loose, in several layers and arranged so that it can be opened up or partly removed to prevent perspiration as dampness from body moisture is one of the greatest causes of freezing. Only small fires were permitted for warming hands or tools as larger fires were more apt to cause perspiration and subsequent difficulty.

"Perhaps the most important lesson learned on construction operations in regions of permafrost is not to change the natural balance and flow of water, particularly in underground channels. In construction of runways it is regular practice not to make cuts, using fills only to attain a level surface. Fills are made largely with gravel from glacial moraine, which acts as an insulating blanket to prevent deeper-than-usual thawing of the ground so that a normal 'balance' is maintained. If deeper-than-previous thawing is permitted to occur, subsidence of the surface is almost certain to follow with subsequent difficulties in airport-maintenance.

"Snow-removal on the bases in Greenland has been a problem comparable to that in the northeastern United States and Canada. Some of the airports have had little snow and others generally have been swept clean by the wind. However, considerable snow has had to be moved from some areas; handling methods and machines have followed practices similar to those used in continental United States. Bulldozers, patrol-graders, and the like have had to be pressed into service due to shortage of specialized machines. On some fields where snow has been severe and removal equipment inadequate, compacting has been resorted to.

"Structures at the bases were built of concrete, wood and steel, all of which had to be shipped from the 'States'. Buildings were designed for extreme winds, with hurricane bracing used to keep them from being blown away. Most of them were built without eaves, as the high velocity wind needed only a finger-hold under the roof to do a quick demolition job.

"Building construction over permafrost had special problems. It was found necessary to keep the footings of buildings and other excavation above the depth to which ground thaws in the summertime, exactly the reverse of what engineers normally would think the proper procedure. The reason for keeping the footings above permafrost is that the water normally flows down along the line between the foundation-structure or replaced fill and the undisturbed earth. This has a tendency to thaw, perhaps only slightly, the frozen material along the contact-line. Since the permafrost contains a high percentage of moisture, occasionally as much as 50 to 60 per cent, even a little thawing causes subsidence and it becomes progressively worse as wider channels are opened up.

"Preferred construction is to build above the ground and to use thick gravel-blankets below foundations to spread the load. An open space now is left below the building-floor to permit air to circulate under the building so that heat is not transmitted to the ground. Double flooring is used and ceiling is added under the joists to keep floors warm in living quarters.

"In general, construction in Greenland was similar to that in the northern part of the United States and Canada except for the foundations. The cold season was generally longer. For most activities, conventional methods of winter building were adequate and were used."

Arctic physics--(a)"Sound effects in polar conditions", by BRIAN ROBERTS [Polar Rec., January, 1944] carries the nature thinker into the realm of vision as well as sound:

"The impressive and all-pervading quietness following a fall of snow is a commonplace experience, though, so far as the writer is aware, only one set of measurements of the sound-absorption of snow has been published. A cold spell in December, 1938, provided a suitable opportunity to make such measurements in the reverberating chamber of the National Physical Laboratory at Teddington, England [G. W. C. KAYE and E. J. EVANS, Nature, v. 14, p. 80, 1939].

"Two specimens of freshly fallen snow were tested, each measuring ten feet square, one approximately one inch thick, and the other four inches thick. The measurements were necessarily

conducted somewhat hurriedly, and the results which are given in the accompanying table for various frequencies from 125 to 4,000 cycles per sec (that is, virtually the speech-range), can only be approximate:

Thickness of snow	Absorption-coefficients for the following frequencies Frequency 125	250	500	1000	2000	4000
1 inch	0.15	0.40	0.65	0.75	0.80	0.85
4 inches	0.45	0.75	0.90	0.95	0.95	0.95

"It will be seen that freshly fallen snow is highly absorbent, its effectiveness being equalled by few known materials of corresponding thickness. In particular, a four-inch layer of soft snow absorbs as much as 90 per cent or more of the intensity of medium and high-pitched notes; and greater thicknesses would no doubt present equally striking figures for low-pitched notes. Thus, apart from the muting of impact noises, the 'deadening' effect of a layer of soft snow can be well understood.

"In the Polar regions, with their natural facilities for producing a cold surface, well-defined inversion-layers are very frequently found as cold, dense layers of air at the surface. In summer, they are often found over glaciers or sea-ice or even over the sea adjacent to well-warmed land-masses. In winter, inversion-layers of varying depth commonly lie over part or all of the land including the ice-covered fjords and sea. In consequence, every degree of abnormal refraction and a variety of mirage-phenomena occur. The same atmospheric conditions which produce optical mirages are also effective in producing acoustical mirages. Whenever the ground-surface temperature is definitely lower than the air-temperature and the gradient upwards is positive, a good range of sound-transmission should be expected. Whenever the ground is warmer than the atmosphere and the gradient upwards is negative, the sound-transmission should be poor. Sound may also be 'scattered' by patches of abnormal acoustic resistance, such as fog, or by solid obstacles.

"These general principles with regard to favorable and unfavorable conditions of wind- and temperature-gradient must be considered in relation to the sound-reflection and absorption-properties of the surroundings. The highly absorbent properties of soft snow have already been noted. A surface of smooth, hard ice, on the other hand, is a good reflector with a very low absorption-coefficient.

"Enough has been said to show that sound is conveyed in a very capricious way through the atmosphere. More than anywhere else in the world, the polar regions provide conditions which sometimes combine to produce one or other extreme."

(b) "Formation and movement of sea-ice" [Polar Rec., January, 1944] brings one face to face with the fresh water on ice-floes so essential to the explorer and the debris on the surface that was once picked up by the bottom of the ice.

"Ice met with at sea is for the most part of two kinds, icebergs originating from glaciers, and sea-ice formed on the sea itself by the freezing of sea-water. Sea-ice proper accounts for probably 99 per cent of the ice met with at sea; bergs are important inasmuch as they constitute a danger to navigation, but they occur only in a limited number of localities. A certain amount of ice may also originate in rivers or estuaries as fresh-water ice, but it is already in a state of decay by the time it reaches the open sea and its importance is no more than local.

"Fresh water freezes at 32°F, but sea-water freezes at various lower temperatures depending on its salinity; the greater the salinity the lower the freezing-point. Average sea-water, with a salinity of 35 parts per thousand, does not freeze in the open sea until the temperature has fallen to 28°6F. The water of the open sea off East Greenland or Spitzbergen, which is somewhat less saline, freezes at about 28°9F.

"If a quantity of water is losing heat at the surface, ice will be formed most readily if the water is fresh, less readily in sea-water of low salinity and least readily in sea-water of higher salinity. The lower-air temperature required to freeze sea-water that is more saline is not due only to its relatively low freezing-point, but also to the increased tendency of the cooling surface-water to sink as the temperature of maximum density decreases. If fresh water cools at the surface from a temperature greater than 39°2F to that temperature, the surface-layer increases in density and tends to sink through the lighter water below.

"Ice forms first in shallow water, near the coast or over shoals and banks, particularly in bays, inlets, and straits in which there is no current, and also in regions with reduced salinity, such as those near the mouths of rivers. It spreads from these areas as centers. Such ice broken up and carried seaward by winds or currents facilitates further ice-formation in deeper water. Ice in deeper water not melted during the previous season also acts in the same way. Wave-action ordinarily hinders the formation of ice to some extent by mixing up the waters of the upper layers. The presence of old ice damps down any sea or swell and at the same time by cooling the water tends to assist the beginning of the freezing-process. The deeper the sea, with waters of salinity less than

24.7 parts per thousand, the later is the time of freezing, or it may never freeze completely, as in the case of the central part of the White Sea. Hence the necessity for following the deep-water route in order to reach high latitudes during the season of ice-formation.

"The first sign of freezing is an oily or opaque appearance of the water, due to the formation of ice-spicules and thin plates about one-third of an inch across, known as frazil-crystals. These consist of fresh ice free from salt and increase in number until the sea is covered by sludge or slush of a thick soupy consistency. Except in sheltered waters, an even sheet of ice seldom forms immediately; the slush, as it thickens, breaks up into separate masses and frequently into the characteristic pancake form, the rounded shape and raised rim of which is due to the fragments colliding with each other. The formation of slush damps down any swell, and if the low temperatures continue, the pancakes adhere to each other, forming a continuous sheet. In pools and lanes of still water the sea freezes direct to black ice. The final result in either case is the so-called young ice, made up of ice-plates about the size of a finger nail, set horizontally in the uppermost half-inch, but otherwise arranged in vertical bundles. Directly formed black ice, three to six inches thick, cracks easily by reason of the plates being set vertically, and a ship can make better headway through it than through the slush and pancake-ice of the open sea.

"While the original ice-spicules and plates are free from salt, a network of ice-crystals forms as further plates are added, in the pockets of which sea-water is trapped. The crystals grow at the expense of the enclosed sea-water; the remaining water thus becomes saltier, and therefore heavier. Rapidly formed sea-ice therefore holds more brine between its crystals than ice of comparatively slow growth. Ice is a poor conductor of heat and the rate of its formation drops appreciably after the first four to six inches have formed; a snow-cover, if present, still further reduces the conductivity. The upper layers are therefore richer in salt than the more slowly formed lower layers. The enclosed brine is itself seldom frozen; it tends to sink through the surrounding crystal-network on account of its density being greater than that of the ice around it.

"Sea-ice may grow to a thickness of three to four inches in the first 24 hours, and two to three more in the second 24 hours. With the subsequent falling rate of growth, ice which has grown steadily throughout the winter is seldom more than four to five feet (1.2 to 1.5 meters) in thickness by the following summer. The original surface of the ice is often below water-level, owing to the weight of accumulated snow, and the original surface of the ice is rarely, if ever, visible after the first few days.

"In the Antarctic the snow-cover remains unmelted during the summer following the original ice-formation, and the slow growth continues. Observers record that surface-floating diatoms work into the ice in summer and are sealed in the ice in autumn. The characteristic resulting yellow layer is a sign that the ice is of more than one season's growth.

"In the Arctic, much higher summer temperatures prevail and the snow-cover melts and runs off or else forms pools of comparatively fresh water. The sea round the floes may thus become covered with a thin layer of fresh water, which spreads under the ice and freezes on the under side. As previously explained, such fresh ice will form in temperatures higher than those required to freeze salt water. In summer, therefore, an arctic floe melts away on top, but at the same time may be slowly growing on its under surface. By this process, mud, stones, seaweed, or shells originally frozen to the under side of grounded floes may work right up to the surface. Diatoms frozen to the under side should similarly rise. An autumn period follows, with lower temperature but without ice formation, the supply of fresh water being no longer renewed and the sea-temperature not being low enough for the freezing of salt water to begin. In the second winter, growth continues by salt water freezing.

"There is a northward tendency in the drift of Antarctic ice, on which a left-hand component due to the Earth's rotation is superimposed. The pack therefore travels westward and northwestward round the Continent, and into and round the Weddell Sea, with a clockwise motion. In the Arctic, the Earth's rotation produces a right-hand component, which also causes the ice to drift westward. The course of the ice is in a great curve round the North Pole from Alaska, via the north Siberian Coast and finally out of the Polar Basin by the East Greenland Current. Some ice also escapes through Smith Sound and Barrow Strait to Baffin Bay.

"In the Antarctic, it is unusual for sea-ice to be more than one to two years old. The drift in both the Weddell and Ross seas carries the pack out into the open Atlantic in little over a year. In the Arctic, floes of much greater age are frequent. Ice formed off the Siberian Coast takes about three to five years to drift across the Polar Basin and down the east coast of Greenland. Ice of this age therefore becomes pressed and hummocked to a degree unknown in ice formed in lower latitudes or in the Antarctic. The warmth of the arctic summers also has its effect and the result is worn-down, more-or-less level, floes of great thickness known as 'polar floes'. The summer melting on the surface is considerable, about two feet as a rule, and pools of fresh water are formed on the floes. This is not a very marked feature off the east coast of Greenland, north of latitude 72° north, but in Baffin Bay the floes of the 'middle pack' become covered with a maze

of deep pools. In the Antarctic, surface-pools on floes in the pack are almost unknown.

"Wind has a direct influence on the melting of ice. Strong wind hastens the process by mechanical action, particularly if the wind-direction is at right-angles to the ice-edge. In the Barents Sea, northerly winds in summer break off pieces of ice and drive them into the warmer water of the North Cape Current, where they melt more rapidly. On the other hand, southerly winds drive the warmer water of this current up to the edge of the ice with the same result.

"The final stages of melting vary with the type of ice. Ice of one winter's growth melts readily in low latitudes, if brine is still present. The internal melt due to variations in the salt-content produces a honeycombed appearance, and the rotten ice so formed soon disappears. Fresher and firmer hummocky ice is longer-lived. Off the east coast of Greenland, polar floes alone reach Cape Farewell, any young or winter ice having melted during the summer passage down the coast. The old floes are heavily undercut at the water-line, but honeycombing is presumably rare, owing to the absence of salt. Underwater rams are produced by the melting back of the uppermost two to three feet of ice. Fresh polar ice should have a fixed melting-point approaching that of fresh-water ice, whereas salty winter ice melts at varying temperatures. In the last stages, hummocky floes may persist as bergy bits, and finally as growlers, greenish in colour, awash, and so are hardly visible.

"The limits of fast-ice are in general determined by the configuration of the shore, its irregularities, and the degree of shelving of the adjacent bottom. Bays and inlets freeze up solid; islands lying near the shore are also usually found within the boundaries of fast-ice. The thaw starts on the shore and at the mouths of rivers. The break-up of the fast-ice is particularly vigorous inshore and along the limits of areas of open water, gradually spreading deeper into the accumulated ice."

Arctic mountaineering--N. E. ODELL, who with H. W. TILMAN made the ascent of Nanda Devi of the Himalaya and has climbed in Spitzbergen and Labrador, has written "Aspects of mountaineering in the high Arctic" [Alpine J., November, 1943] and HENRY S. HALL, Jr. [Appalachia, June, 1943] has discussed "Exploration of mountains near the Alaska Highway" [quoted in Polar Rec., January, 1944] as "something not to be lightly undertaken. . . .

"The new road built by United States Army Engineers from Fort St. John, British Columbia, to Fairbanks, Alaska, 1670 miles in eight months (March-November, 1942) is, in the opinion of the people who know the country, one of the remarkable achievements of this war. The road was built principally for emergency war-use, and consequently scenery was, if anything, avoided. . . .

"For those who are familiar with the magnificent sea-voyage to Alaska, the new road will be worth driving over for a change. It is likely, however, that the scenery along it will prove disappointing to many who know the coastal route or other areas where it is easy to see great mountains, glaciers, and cliffs without being rebuffed for much of the distance by dreary foothills."

The Northwest Passage-- The mastering of the Northwest Passage by the St. Roch in 1940-42 is the first voyage by ship around Arctic America from west to east and the second through trip from either direction. But these claims are technical rather than actual for ships have met in the center of the Passage from either direction and returned to their bases. This fact is presented by The Polar Record [January, 1944] under the title "Voyages through the Northwest Passage."

"The only two ships which have yet completed a Northwest Passage are the Gjöa, from east to west in 1903-07, and the St. Roch, from west to east in 1940-42. An account of the latter voyage appears on pages 115-118 of The Polar Record.

"In 1928, the Hudson's Bay Company auxiliary schooner Fort James set out from St. John's Newfoundland, to make the Northwest Passage. Like the Gjöa, she spent two winters at Gjöa Haven, King William Island, and while she was there she was met by the Hudson's Bay Company schooner Fort MacPherson coming from the Canadian western Arctic. In 1930 the Fort James returned to her regular work of visiting the eastern Arctic posts. Four years later she was transferred, via the Panama Canal, to the western Arctic, and reached Cambridge Bay, only 225 miles west from her wintering place of 1928-30. She therefore almost circumnavigated the North American Continent, but did not make an actual Northwest Passage.

"In 1937 the Nascopie from the Atlantic met the Aklavik from the Pacific at Fort Ross in Bellot Strait. They exchanged furs and put about again to return to their home ports, thus making commercial use of the Northwest Passage for the first time [see Polar Rec., pp. 39-42, January, 1938].

"In 1938 the Nascopie met the Aklavik at Fort Ross, thus again making a 'virtual' Northwest Passage, but as in the previous year both ships returned to their home ports [see Polar Rec., p. 52, January, 1939]."

Arctic manuals--The following publications have been received from Dr. LAURENCE M. GOULD, Chief, Arctic Section of the Army Air Forces, and Member, Committee on Snow, American Geophysical Union, which represent in their titles the effort made to safeguard the Army Air Forces in the Arctic: Survival; The Arctic; Arctic manual; Emergency living in the Arctic; Care of personnel in the Arctic; Aircraft operations in the Arctic; The mosquito and fly problem in the Arctic; Arctic maintenance of air craft.

Transport

Highway- and airfield-problems--(a) The winter maintenance of the Alaska Highway is a problem of removing accumulating ice rather than snow. As expressed by HAROLD W. RICHARDSON, Western Editor, Engineering News-Record [January 27, 1944], "Despite the severity of the weather, with temperatures reaching 72° below zero, the road was kept open all last winter. Snow caused little trouble, and there was plenty of snow-removal equipment on hand to take care of the few bad spots in the high passes. Ice was much more troublesome. All through this north country lie underground ice-sheets, even on the steep slopes. On the hillsides, especially where disturbed by side-hill cuts, they continually bleed water, which soon freezes upon striking the open air, building up ice-sheets that fill the side ditches, clog culverts, and pile up on the road. Constant chipping kept the road open in most places, but temporary by-passes were required in others. No permanent solution has been found for such conditions, but bigger culverts, wider ditches, and raising of the roadbed all help. Some culverts were kept thawed out with live steam. Additional thawing equipment has been made available for this winter's operations in hopes of avoiding much of the trouble.

"River-ice also caused considerable difficulty last winter, particularly in the glacial streams of western Yukon and Alaska. Because the subsoil is permanently frozen, these shallow streams start freezing from the bottom in the fall. As a channel clogs up with ice, the stream jumps to another channel in the wide, boulder-strewn valley, thus working back and forth, building the ice higher and higher. At Robertson River in Alaska, for example, the ice built up to ten feet above the deck of the temporary trestle; the road had to be maintained on top of the ice."

Thus despite the jibe of "sky-hooks", elevation of the road at critical spots may ameliorate the perennial plague of mud or ice.

(b) Snow-Removal--The caterpillar tractor is becoming the acknowledged master of extreme situations in traversing snow or removing it.

The following titles to illustrations in Caterpillar Magazine [issue 88] are truisms: "Up where it's cold! Four feet of snow, one foot of frost"; "Up near timber-line, United States Vanadium Corporation uses this 'Caterpillar' Diesel D7 Tractor--equipped with an Angledozer--to push a road up a mountainside, through four feet of snow and one foot of hard-frozen ground"; "Blitzing a blizzard: Working for the city of Halifax, Nova Scotia, this Traxcavator-equipped Diesel D4 tractor scoops up snow, 3/4 cubic yard at a 'bite', lifts, carries, and dumps the snow into trucks for out-of-the-way disposal. Thus in a single day, a one-man 'blitz' on a blizzard can scoop the drifts from blocks of sidewalks, street curbings, or war-vital freight-loading docks." (See Fig. 4)

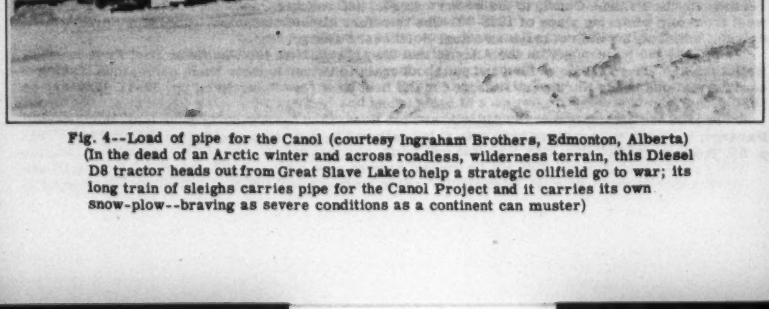

Fig. 4--Load of pipe for the Canol (courtesy Ingraham Brothers, Edmonton, Alberta) (In the dead of an Arctic winter and across roadless, wilderness terrain, this Diesel D8 tractor heads out from Great Slave Lake to help a strategic oilfield go to war; its long train of sleighs carries pipe for the Canol Project and it carries its own snow-plow--braving as severe conditions as a continent can muster)

Snow-removal by heat--Under the impetus of air-commerce, both military and civilian, special effort is being made to keep airfields clear of snow and dry. In this effort, snow-removal is being supplemented by heat. This project has already been mentioned in the Report of this Committee for 1941 [Trans. Amer. Geophys. Union, p. 968, 1941]. J. B. SWEENEY, Director of the Allegheny County Department of Works, Pennsylvania, to whom the progress is due, has provided further details:

"I have read recently your most interesting series of articles on 'The human side of snow' in The Scientific Monthly. I was surprised indeed to learn that there is in existence such a mass of detailed information on the subject as you have compiled.

"My own interest in the subject of snow originated in the fact that I have been for several years responsible for its removal from the large County Airport runways near Pittsburgh, as well as from the County highway-system of nearly 600 miles. This responsibility resulted in my study of the question of snow-removal by melting and the development of a machine for the purpose. These activities have extended over a period of four years and have produced, by experiment and trial, a machine which indicates a successful solution of a problem which is of great practical concern now and probably will be even more so in the future.

"Our problem here is of course small in comparison to the large amounts of snowfall with which you are so familiar, but the problem is emphasized here due to the large population and traffic volume, both by airways and highways, in this vital war-production area. My interest, of course, originated primarily in my responsibility as a public official. But now, to speak frankly, I must admit a selfish interest to make my invention, on which I have expended a large amount of money, a practical and financial success.

"The machine referred to in The Engineering News-Record [February 6, 1941] has been rebuilt, with numerous improvements, and has proved a success. Now I have reached the stage at which I am subjected to numerous questions as to its operation and to statements I have made in connection with its manufacture, use, capabilities, etc.

"Believing that you will have a public interest in this invention, I am taking the liberty of enclosing herewith a brief description of the machine and its possibilities, and two illustrations (Figs. 5 and 6). I shall greatly appreciate any comment you may care to make as to statements of fact in the description.

Description of Snow-Removing Machine (J. B. SWEENEY)--The object of this machine is to apply heat to remove (and keep removed) snow and ice from airport runways, highways, city streets, and other paved areas, street railway tracks, etc. Smaller machines, using the same principle, will prove valuable also for snow- and ice-removal from sidewalks and automobile service stations. By adding accessories, the machine will open frozen drains, manholes and fire hydrants, and melt snow and ice on any surface to which the heat is applied.

The old type of machine, which depended merely on pushing the snow to one side, was able to do little in the way of snow-removal until at least two inches of snow was lying on the pavement. With this new snow-melting type, operation is started when the snow begins to fall, or even, if advance knowledge of the snow is given by the Weather Bureau, before the snow begins.

The traveling speed will depend upon the work to be done. If operation is begun at the start of the snowfall, the speed for the first hour should be 15 miles per hour, then reduced to suit the conditions presented by the particular storm. It has been demonstrated by tests, however, that the average speed should be about ten miles per hour.

Although primarily designed for snow-removal by melting, the machine is equipped also with a snow-removal blade. This blade, 15 feet long by 34 inches in height, permits the machine, in an emergency, to be used as an ordinary snow-plow. This blade also will serve for the removal of excess snow if for any reason it is not possible to start melting operations at the beginning of the snowfall, and for the removal of drifts encountered.

The Snow-Removing Machine consists of any standard grader upon which is suspended a steel combustion-chamber properly insulated, with vents to permit the fumes to escape, five oil-burners, a pilot-light for each burner, a blower, a gasoline engine to operate the blower, a fuel-meter which records the number of gallons of fuel-oil used, a pressure-gage to indicate the pressure of the oil, a two-way radio set for communications to and from the control-tower, an excess snow-removal blade which is placed ahead of the grader and which is similar to any standard snow-plow. In order to dry up any moisture that might be left after the combustion-chamber has passed over the surface, the exhaust heat, fumes, etc., are collected and directed to the surface at the rear of the combustion-chamber, and are given additional acceleration and pressure by means of the air-blowers.

One of these machines is designed to take care of more than one-half of a regulation Army runway, 84 feet wide and approximately 6,000 feet long, which represents 504,000 square feet of surface.

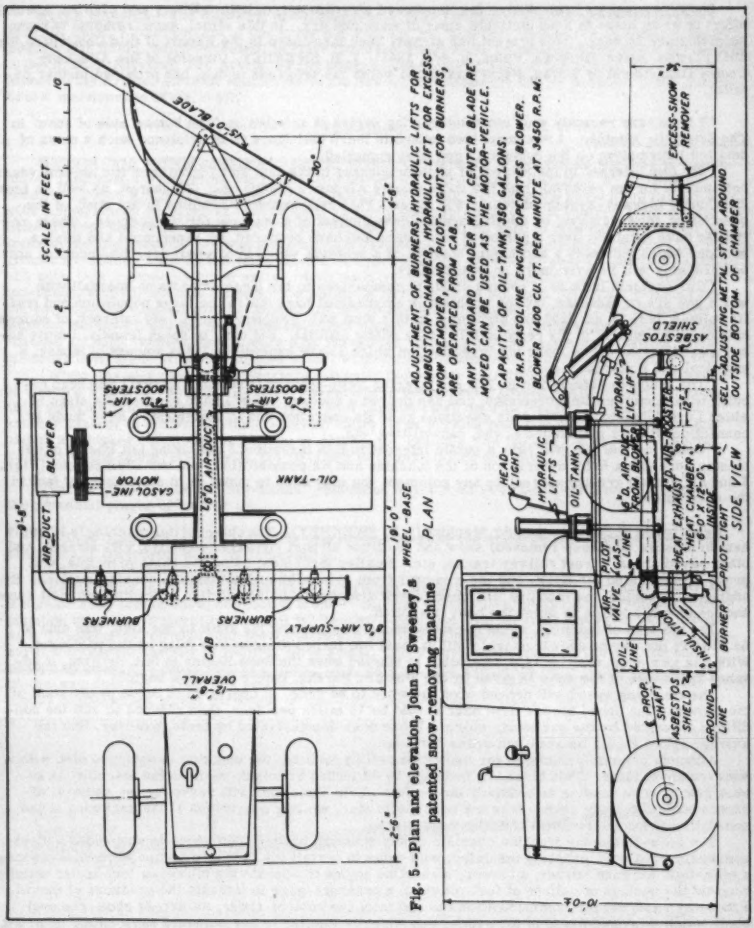

Fig. 5--Plan and elevation, John B. Sweeney's patented snow-removing machine

According to information received from the Weather Bureau, the maximum rate of snowfall in the United States is one inch per hour. Using this figure, and assuming a six-inch snowfall, there would be 9,333 cubic yards of snow on this runway were it allowed to accumulate before the Snow-Removing Machine is started. But by starting the machine with the snow, or when a Weather Bureau report indicates that the snow will start to fall within one hour, it will be possible to keep this snow removed as it falls and not permit it to stay on the surface, as the pavement will be kept above the freezing-point (32°F).

The estimated cost of operation for eight hours is $62.40, or two-thirds cent per cubic yard.

Operation on an airport runway--Snow usually does not begin to lie on a paved surface until from 15 to 45 minutes after the snowfall begins, 30 minutes being the average time, as the snow first melts as it falls. The water produced by melting is mostly absorbed by the pavement but some also is lost by immediate natural evaporation. Therefore, if the machine is put into operation immediately as the snow begins to fall, it at once begins to evaporate the water and also tends to keep the pavement above the freezing-point. The area covered by the machine before it encounters snow will depend on the speed of operation, but the elapsed time will average 30 minutes.

Thus operating at a speed of 15 miles per hour (which is not excessive at the beginning of a snow) practically the whole 504,000-foot area will be covered before any snow is encountered on the runway. Even at the low speed of eight miles per hour, one-half the runway will be covered without encountering any lying snow.

If, after continued operation, any drifts should be encountered, they can easily be taken care of by the excess snow-removal blade, as they would only have to be pushed off to one side, a maximum movement of 84 feet.

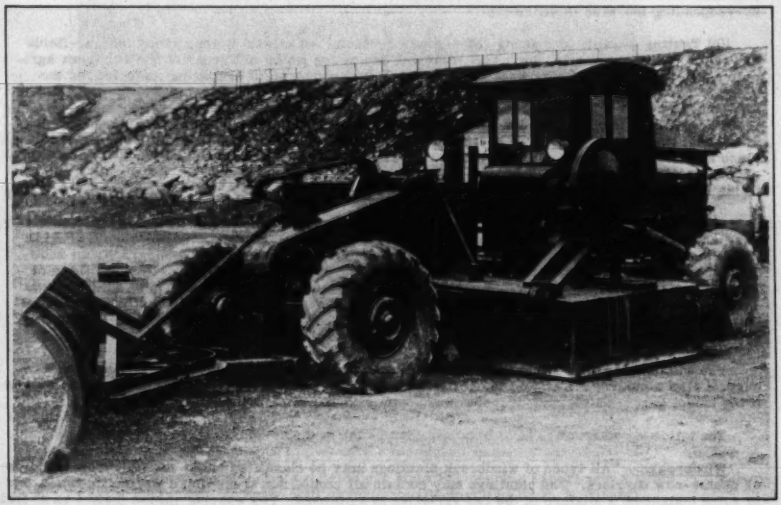

Fig. 6--Snow-removing machine (courtesy John B. Sweeney)

Operation on a 20-mile road--As another example of the machine's power, assume a 20-mile length of two-lane 24-foot highway, on which a six-inch snowfall would produce nearly 47,000 cubic yards of snow to be removed. But by starting operations with the beginning of the snowfall, and traveling at ten miles per hour, the maximum depth of snow to be removed at the end of the 40-mile run would not exceed 3-1/2 inches. This depth would be removed easily by the excess snow-removal blade to a depth of 1/8 inch above the pavement, which would quickly disappear under the hot blast from the combustion-chamber. If the snowfall continued, the machine would be kept operating until all snow had been removed. For eight hours' operation the cost would be $62.40 as on the airport runway above cited. The cost of this operation would be $3.12 per mile of two-lane highway, or about 1/7 cent per cubic yard to remove snow and keep the pavement free of ice.

No damage to pavement from heat--The question sometimes is raised as to the possibility of damage to the pavement, particularly if of bituminous material, by the hot blast from the machine. There is no damage. Actual operation has demonstrated that, with the machine traveling at as low a speed as eight miles per hour, it is not possible to raise the temperature of the pavement surface

to above 58°F. When the machine is stopped, the combustion-chamber can be raised in five seconds by the hydraulic lifts to 12 inches above the pavement, at which height there will be no damage with the burners and blower in full operation.

No water-residue--The impression is erroneous that an enormous amount of water is formed that may cause difficulty in disposal. From investigation and experiment, it has been found that the water-content of a newly-fallen snow-crystal is only about three per cent of its actual volume. This small water-content disappears by absorption into the pavement and evaporation by the heat from the combustion-chamber. As to the possibility of the formation of a film of ice on the pavement, observations by engineers over a period of many years have established the fact that the average water-content of snow lying after it has fallen is only about ten per cent of its depth. Since the snow will be removed down to a 1/8-inch depth by the excess snow-removal blade, the maximum film of water resulting from this 1/8-inch depth of snow would be only 1/80 inch. This amount would not be sufficient to form a film. Furthermore, by continuing the use of the machine for not more than two hours after the cessation of the snowfall, the pavement would be kept absolutely dry.

All-year-round machine--This machine can be converted from a snow-removing machine to a grader in four hours (at a cost of not more than $20) making it an all-year-round machine with corresponding increase in efficiency.

(c) Testing stability of thawing soil--A new problem has arisen at emergency landing-fields says C. E. RAMSER [Agric. Eng., May, 1944]. "One of the major activities at the Michigan Agricultural Experiment Station at East Lansing, Michigan, consisted of preparing material for the Weather Directorate of the Army Air Forces, Washington, D. C. The Directorate is interested in analyzing these data in order to learn of the rate of thawing of frozen soil. Such information is of fundamental importance in the operation of unpaved emergency airfields in the north country. It is known that the impact of landing wheels on heavy aircraft often amounts to many tons per wheel. Since a freshly thawed-out soil is apt to be water-laden beyond its soil-capacity and, because of processes of freezing and thawing, in a structureless condition, attempts to use unpaved landing-fields immediately after thawing of the surface-layers of the soil may entail tremendous risk."

(d) Snow-control--In complying with the request of Dr. E. BUCHER, Director of the Swiss Snow and Avalanche Research Station, Weissfluhjoch, Davos, Switzerland, sent through GERALD SELIGMAN of England, the Chairman has had opportunity to transmit three monographs on snow-control by E. A. FINNEY of the Engineering Experiment Station of the Michigan State College of Agriculture and Applied Science. These are "Snow-control on the highways" (now out of print), "Snow-control by tree-planting", and "Snow-control by highway-design". Having been published between 1934 and 1939, they deserve to have been reviewed by the Committee long since, for they are comprehensive.

The wind-tunnel experiments on tree-plantings and air-flow over highway cross-sections suggest also a method of studying the relative accuracy in catch of precipitation-gages, particularly if the model gages can be made transparent, as of cellophane. (See Figs. 7-A and 7-B.)

The following summaries have been provided by the author:

Windbreaks--"All types of windbreak plantings may be classified under multiple-row barriers or double-row barriers. The plantings may contain all coniferous trees or all deciduous trees, and in some instances, a mixture of the two varieties is employed. The spacing varies from 4 to 25 feet in rows spaced from 5 to 20 feet apart.

"Numerous investigators claim the effective area of a wind-barrier to be from 10 to 50 times the height of the barrier. This great variation is no doubt due to many factors existing in the barrier. An average value of 15 times the height of the barrier was obtained from wind-tunnel tests using model trees.

"Wind-velocity has no effect on the size of the eddy-area produced by a barrier, but it does affect the position of the drift with respect to the barrier. A high wind causes a strong back current on the lee side of a barrier which tends to move the snow towards the barrier depositing it next to the trees. Low wind-velocities allow the snow to be deposited the entire length of the eddy-area. This is only true for tight or dense barriers. Open barriers allow the wind to filter through the trees and at high velocities the snow is carried away.

"Best results were obtained when the spacing of the trees and the rows was the same. The trees should be staggered in the rows.

"It is not necessary to plant more than three rows of trees for effective snow-control. Two rows of trees will be very effective if properly planted.

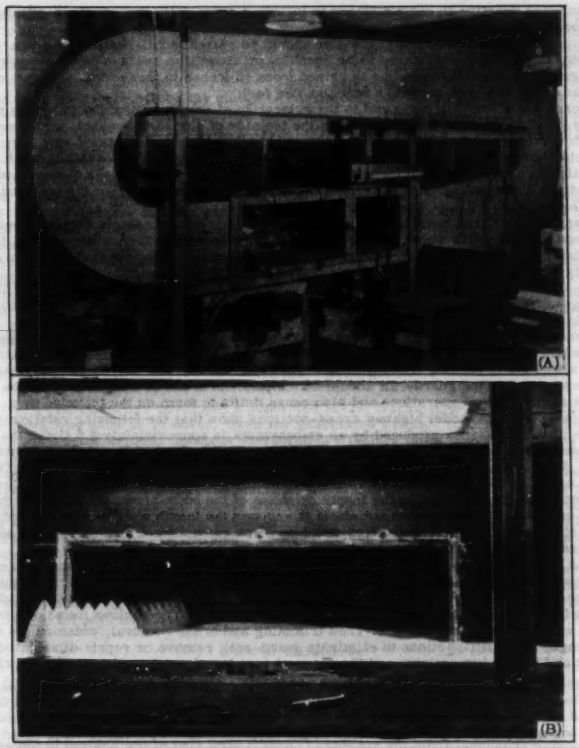

Fig. 7--Wind-tunnel experiments at Michigan State Engineering Experiment Station: (A) Wind-tunnel; (B) snow-drift experiment (Photographs by E. A. Finney)

"The spacing of the trees can vary with the number of rows. The spacing should be close for a single row and not more than twice the diameter of the crown when three or more rows of trees are used. Best results are obtained when the tips of the branches of the trees are just touching.

"Flowering shrubs are being considered as material for snow barriers."

Highway-design--"A review of the work being done in the various States shows quite definitely that highway-design methods can be employed effectively to reduce snow-drifting on the highways. The present trend towards cheaper costs of excavation, railroad grades, wider right-of-way, and highway beautification has added greatly to the ease with which the design for snow-control features may be incorporated into highway practice.

"It may be said that special design features for snow-drift control consist essentially of the following: Raising the grade-line to a definite position above the adjacent ground-line, avoiding cut-sections, special treatment of cut-sections, the adoption of wide shoulders, flat backslopes, and shallow ditches, the use of vertical curves at the top and bottom of slopes, elimination of guard-rail where possible, and the relocation of existing routes.

"It is standard practice in certain States to include a snow-drift study in the preliminary survey of new construction.

"The proper height to which the grade-line should be raised in fill-sections and in areas of flat topography is generally considered to be equal to, or above, the average depth of snowfall. Under average conditions the grade-line is raised from 18 inches to three feet. In areas of heavy snow, the grade-line has been raised as much as five feet.

"In the creation of new highways and in the relocation of existing ones, the following practices are generally considered: (1) In rolling country the lee side of slopes is avoided, high ground and windward side of slopes are resorted to where possible; (2) on narrow rights-of-way deep-cut sections are avoided and especially when the highway is perpendicular to the prevailing winds; (3) the highway location is usually selected through sheltered areas such as in valleys and wooded areas; (4) farm buildings and dwellings are either avoided or moved far enough from the traveled way so that their influence area will not cause drifting on the highway.

"Shoulders, ditches, and backslopes are being designed to provide ample storage-space for snow-plow deposits and drifts which are formed from wind-borne snow. A width of eight feet is considered standard practice for shoulders, however some States are using ten feet and even eleven feet especially when guard-rail is to be eliminated on high-fill sections.

"In deep-cut sections, it is common practice to borrow fill-material from each side thus creating a storage-space for snow-deposits. Some States make a standard practice of widening all cut sections at least ten to fifteen feet to provide snow-storage.

"It has been found that rounding the top and bottom of embankment slopes greatly improves the general appearance of the highway, eliminates soil-erosion and reduces maintenance-costs. Rounding the slopes will aid in causing free air-flow across the highway and consequently reduce drifting.

"Wherever possible the guard-rail should be omitted. In areas of heavy snowfall the guard-rail will limit snow-removal operations and also cause drifts to form on the traveled way.

"Wind-tunnel tests on model highway cross-sections show that the following relationships exist: (1) The length of the eddy-area produced by an embankment is approximately 6.5 times the height of the embankment. This relationship will vary somewhat with the slope of the windward side of the embankment. Wind-velocity has no effect upon the length or shape of the eddy-area. (2) The fundamental shape of the eddy-area formed by an embankment is ichthyoid in character. (3) The slope of the embankment face does not change the length or shape of the eddy-area. (4) Rounding the top and bottom of the embankment slopes does not affect in any way the length and shape of the eddy-area. (5) From the standpoint of minimum drifting, the face of an embankment formed by a cut should have a slope not steeper than 1 on 4. The same is true for an embankment formed by a fill.

"There is need of an organized highway-betterment program to eliminate areas of excessive snow-drifting and by so doing improve the general appearance of the highway with consequent decrease in snow-removal costs. The worst conditions exist on the county and township roads where in most cases funds are not available for doing this type of work. The various items of work to be considered in a betterment-program are: Tree trimming and brush removal; widening cut sections for snow-storage; widen fill-sections to eliminate guard-rail; remove or repair dilapidated right-of-way fences and other obstructions; and the frequent mowing of weeds and grass on the right-of-way."

Mudding sled-runners

It is a long development from the muskeg- ("mud") shod sled of the Eskimo to the amphibian motor sled of the Army. Yet both are described in current literature.

Under the title "The mudding of sledge runners", Venerable D. B. MARSH [Beaver, March, 1942; reprinted Polar Rec., January, 1944] describes the process of applying the universal muskeg to the primitive sled. He says: "For generations the Eskimos have used 'mud' as a shoeing on the runners of their sledges. The term 'mud' does not mean the same in the Arctic as it does to those who live farther south. In the north mud is muskeg or decayed mosses and vegetable matter. Light in weight, it can be planed smooth and covered with a coating of ice, so that sledges so shod slip lightly and easily over the Arctic snows. Perhaps its greatest advantage is that it can be found almost anywhere in the Arctic and thus repairs can be made at any time and place. Good mud must be totally free from sand and grit, and sufficiently decayed that it can be broken up till it resembles a fine meal.

"As soon as there is enough snow on the ground, the Eskimos start to mud their sledges, and in the fall when the temperature is above zero it is a much more pleasant job (though never really pleasant any time) than when the temperature registers 40° below zero.

"The top layer of the frozen ground is first removed, and the soft water-logged underlayer chopped fine with an axe or snow-knife before the Eskimo sets to work mashing the mud with his hands to make it evenly textured throughout. In the winter, the mud is chopped out with an axe, then thawed and broken finely within the shelter of an igloo or windbreak.

"From this 'mash' he makes a ball of mud with his hands and carries it on to the sledge, where he breaks it in half. One half is laid on the runner out of the way and the remaining portion taken in both hands. This he splits in two, and holding a part in each hand, applies them to opposite sides of the runner. Using his fingers to mould the sides, his thumbs press and shape the top surface, and when finished, the other half of the original ball is used in the same way. Many trips to the mudhole are necessary before the sledge is completed, and when several men are mudding together, the first one finished will often help his companion. The job completed, the mud is left to freeze--often overnight--but if the Eskimo feels certain that the night will be cold and the mud is frozen before sundown, he will plane it before dark.

"For planing a sled, a modern jack-plane is used, though in former times a block of wood with a piece of steel inserted for a cutter served admirably for this purpose.

"Icing is the next operation; and for this water is taken from the ice-hole and either poured from a vessel or else taken into the mouth and squirted into a piece of bearskin. The bearskin is then rapidly swept over the surface of the mud, leaving behind it a thin film of water which freezes almost immediately.

"The thickness of ice laid on the runners depends entirely upon the judgment of the Eskimo who is icing the sledge and his knowledge of the type of country over which he is to travel, together with the likelihood of the ice rapidly wearing off in comparatively warm weather. Needless to say, gravelly or rocky ground or rough ice will not only wear off the ice but often knock large pieces of mud from the runners. Thus a sledge may need to be iced many times a day, and it is seldom that it is not necessary to do it at least once at midday."

Amphibian sleds

The War Department has developed a supersled M-29, tractor-type light cargo-carrier, that travels on land, ice, snow or in water. Says the Associated Press, "It looks like an old-fashioned iron bathtub on tractor-treads. Its most extraordinary feature is its operation without an occupant.

"In country where dangerous crevasses are hidden under breakable snow-crust, the M-29 can be operated by a driver skiing or snow-shoeing 50 feet to the rear of the vehicle. If the machine breaks through the snow-crust, only the machine is lost and highly-trained manpower is spared. In this use the operator guides the vehicle with rope reins attached to the M-29's steering levers.

"The machine is the mainspring of the Army's Arctic Training Program at Echo lake near Denver, where selected men are learning to service planes in frigid climate, perform Arctic rescue missions and find their own livelihood in desolate, snow-covered areas.

"This vehicle will carry 1,200 pounds and tow a trailer or a half-hundred men on skis.

"Last winter Major C. A. K. INNES-TAYLOR, Arctic explorer of the Byrd Expeditions and Chief of Arctic Training, and BELMORE BROWNE, the famed artist-explorer, took the buggy on a 500-mile trip through the Canadian Rockies."

Cars on snowshoes

The following advertisement in Time [October 30, 1944] shows how rubber is keeping pace with sleds: "When there was danger that the Japs might invade Alaska, the Army needed a new kind of vehicle to travel fast on deep snow--or on ice, through water, swamps, or on hard roads. It had to have 'tank-treads', not wheels, and it had to be so light it would 'float' on snow. B. F. Goodrich (Company) men had developed light rubber-covered treads for 'half-track' vehicles, but even those were too heavy. Could they be made much lighter? Could 'fins' be added to push against snow, but which still wouldn't touch ground on a hard road? Could they get the answers quickly?

"For fastening rubber to metal, rubber men had always used molds--and molds took six months to make. B. F. Goodrich (Company) developed a method of blowing the rubber on the metal with compressed air. It was faster and worked just as well. They designed new treads while an automobile company was designing the machine itself. The 'weasel', as it is called, is just about the fastest thing off wheels. They used it in France instead of Alaska, but the snowshoes turned out to be the best kind of sandshoes and mudshoes (Fig. 8).

Winter transportation in the high Sierra by "Sno-Motor"

But snow-motor vehicles not required by war needs are being still further improved for special tasks. The massive "Sno-Motor" of the Southern California Edison Company still satisfies as shown by the following solicited report by W. A. LANG:

"A report on the Edison Company's operation of the Sno-Motor up to the end of 1941 was presented at the Pasadena Meeting of the Western Snow-Conference on January 16, 1942 [Trans. Amer. Geophys. Union, pp. 161-163, 1942, illus., and p. 971, 1941]. In the last two years additional

Fig. 8--Car on snowshoes (courtesy Studebaker Corporation)

operating experience has been gained as outlined in the following paragraphs.

"Since January, 1942, the Sno-Motor has been driven 956 miles with an output of 1.09 miles per gallon of gasoline. The total operating time was 245 hours. The operating cost exclusive of depreciation and the charge for the driver, but including gasoline, oil, and repairs, has averaged $1.26 per mile for the last two years.

"The value of the Sno-Motor to the Southern California Edison Company has been amply demonstrated. In the early spring of 1942 it was necessary to transport 35,000 pounds of 12-gage steel sheets 48 inches by 96 inches in size, 31 miles from Big Creek to the Florence Lake Dam. The sheets were to be used in repair work which had to be completed before the spring runoff filled the reservoir. These steel sheets were hauled across Kaiser Pass at 9,300 feet elevation between April 30 and May 13 while the roads were still covered with up to 105 inches of snow. In addition to handling the steel during the spring of 1942, the Sno-Motor transported the repair crew with necessary supplies and food during the months of March, April, and May of 1942 and 1943. The maximum snow-depth during these periods was 161 inches.

"On account of the illness of one of the Florence Lake headworks tenders, an emergency trip over the same route was made in January, 1944. A man to replace him together with complete winter supplies was transported on the inbound trip and the headworks tender's wife and personal belongings were brought out on the return trip. The round trip was made January 11 and 12 with no difficulty whatever.

"Our experience indicated that this type of vehicle is more desirable than smaller types which cannot carry a sufficient load.

"Taking the operation of the present Edison vehicle into consideration during the period owned by the company, everyone connected with the operations of the power-plants seems to be fully sold on its value, but like every other type of machinery new developments and improvements will no doubt make models now in operation obsolete.

"The designer of the Sno-Motor, TED FLYNN of Portland, has developed a new type very similar to the Edison Company vehicle, except that it is a two-track machine, is considerably lighter, and has a somewhat smaller capacity. The two tracks permit much quicker steering.

"It is our understanding that one of these new types has been delivered to the Bonneville Power Administration for maintenance of its power-lines. The design is expected to incorporate on the vehicle some sort of winch by which the repair crews might be able to hoist such repair parts as necessary to the top of the transmission-towers when needed under snow-conditions.

"The designer of the new Sno-Motor, two-track model, and sled, makes the following claims for improvements: (1) Easier and quicker maneuverability in tight places; (2) with greater track-area, and relatively lighter weight, it has greater tractive ability on soft snow and steeper grades; (3) the new track-system mounting provides greater freedom for tracks and consumes noticeably

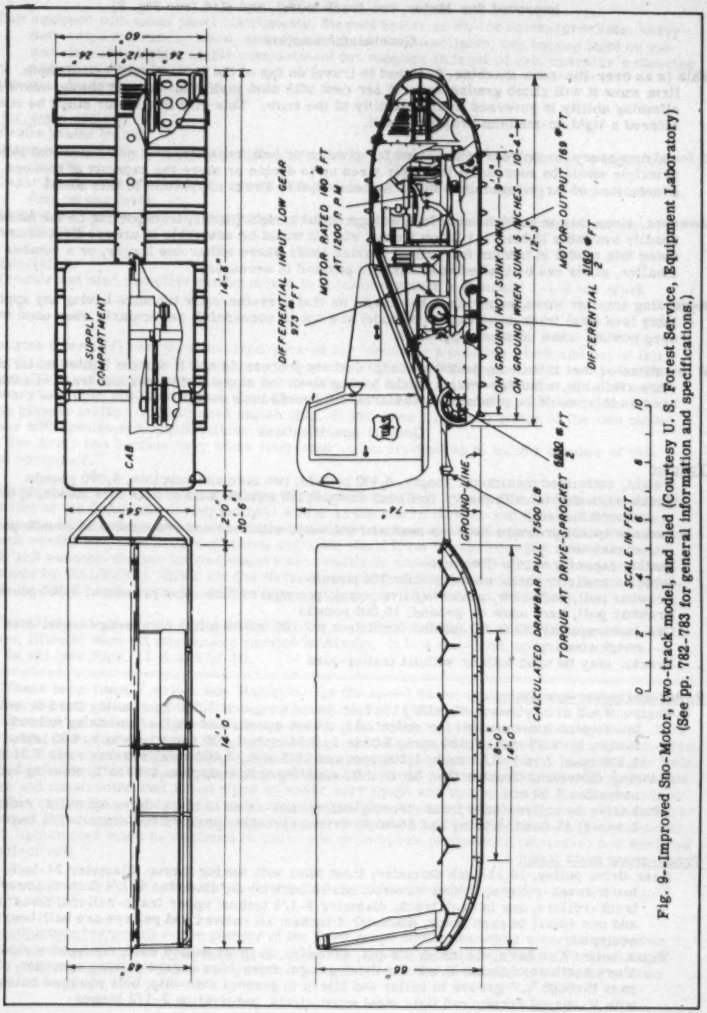

Fig. 9--Improved Sno-Motor, two-track model, and sled (Courtesy U. S. Forest Service, Equipment Laboratory)
(See pp. 782-783 for general information and specifications.)

Improved Sno-Motor, two-track model, and sled (see Fig. 9)

General information

This is an over-the-snow machine, designed to travel on top of the snow regardless of depth. On firm snow it will climb grades up to 55 per cent with sled payloads. On soft powder-snow its climbing ability is governed by the stability of the snow. This size Sno-Motor might be considered a light-to-medium cruiser-model.

If found necessary to consider other sizes for greater or less capacity, it is estimated that this principle would be successful in larger sizes up to double or more the capacity of this one. Dimensions of larger machines would be somewhat in direct proportion to this model.

However, since this is an ideal size for getting around in tight places, transporting on the more readily available lighter 1-1/2 ton trucks, etc., it would be advisable to always first consider using this model in tandem for pulling heavier loads where either one larger, or a number of smaller, sleds can be trailed where larger payload is necessary.

Regarding smaller sizes, experience has taught us that over-the-snow tractors having any appreciably less total track-area than this model are not as successful, particularly when used in deep powder-snow on steep upgrades.

It is estimated that if built in quantities under factory processing and if certain lighter materials were available, a feather-weight model having about the same track-area and tractive advantages as this, could be produced with 500 to 700 pounds less weight.

General specifications

Tractor

Weight, estimated maximum: Empty, 4,400 pounds; two men and supplies, 5,000 pounds
Track-area contact with snow: Not sunk down, 5,180 square inches; sunk five inches, 5,450 square inches
Average track-pressure between sunk and not sunk, with load and two men: 0.84 pounds per square inch
Seating capacity of cab: Two men
Supplies capacity comp. ahead of cab: 200 pounds
Drawbar pull, soft snow, assuming five pounds per square inch snow pressure: 5,000 pounds
Drawbar pull, hard snow or ground: 10,000 pounds
Gas-tank capacity: 40 to 50 gallons (sufficient for 100 to 160 miles on average travel over rough country)
Tractor may be used with or without trailer-sled

Power and power-transmission

Engine: Ford six-cylinder, 90 BHP, 180 foot-pound torque at 1,200 rpm, using Ford or equal four-speed transmission for reductions, travel-speeds and engine-speeds as follows: 6.40 to 1, 1.27 mph, 1,200 rpm; 3.09 to 1, 2.64 mph, 1,200 rpm; 1.69 to 1, 4.80 mph, 1,200 rpm; 1 to 1, 8.11 mph, 1,200 rpm and 20.3 mph, 3,000 rpm; reverse ratio 7.81 to 1
Steering: Cleveland Tractor Co., M. G. diff. steering unit, reduction 3.50 to 1, steering-axle reduction 1.80 to 1
Final drive by roller-chain from steering differential-axles to track-drive sprocket, reduction 2.4 to 1, 15-tooth driving and 36-tooth driven sprocket, pitch roller-chain 1-1/4 inch

Track-group main items

Rear-drive pulley, 19.11-inch diameter; front idler with spring takeup, diameter 24-inch; lower track-rollers, rubber covered, six in each track, diameter 6-1/4 inches; lower track-rollers, one in each track, diameter 9-1/4 inches; upper track-rollers, three plain and one spiral in each track, diameter 4 inches; all rollers and pulleys are ball-bearing equipped
Track-belts: Two belts, Goodrich six-ply, 42-ounce, each 24 inches wide, equipped inside with short sections of Gates E belt for driving lugs; drive-lugs engage driving sprocket, also pass through _/-groove in roller and idlers to prevent side-slip; belt equipped outside with V-shaped reenforced light steel snow-cleats, penetration 2-1/2 inches

Cab

Cab equipped with usual panel instruments, Stewart heater to de-ice drive-sprockets, heavy-duty swipe for rain or snow, non-shatter glass, two headlights, one backup light on cab and clearance lights, ample compartment for supplies in front of cab, operator's steering and other controls

Drawbar for towing extends from dead axle

Sled for extra payload

Trails behind tractor

Dimensions: Width, 48 inches; length at top, 14 feet; length on ground nine feet; weight, 500 pounds

Capacity: Freight type of load, up to 1,800 pounds; men with supplies, five to six; stretchers, four on one level

Removable canvas-covered top; folding seats; spruce runners; sled constructed mostly of plywood

Transportation

Tractor and sled complete can be moved to point of use with a standard 1-1/2 ton truck

less engine power; (4) has provision incorporated for installing a hoisting winch and set of fair-leads; (5) increased room in cab with no increase in weight and added good sized compartment for baggage; (6) an outstanding advantage is that the machine can be operated without the sled when necessary and when operated alone, should have greater ability for grades, etc., and also for making pioneer trails. The attached sketch (Fig. 9) indicates a general design of the new model together with details and specifications.

"The Army has become very much interested and is proceeding to build a number of this type of equipment."

An Alaskan air-propelled sled and the Tucker Sno-Cat (Fig. 10) have come under the immediate notice of the Chairman during the past winter in the Sierra Nevada and he has ridden many miles on the latter, which is an ant in its relatively prodigious ability to carry and draw loads. It can back readily and with little assistance extricate itself from break-throughs. Fenders, windshield, and weather-shelter for passengers can readily be added. A color film of its action has been made by WALTER J. HERZ for the Nevada Agricultural Experiment Station. Earlier reference to this sled has been made in these Transactions [pp. 161-163 and 425, 1942].

The Alaska air-sled was designed by RALPH P. HANSON (5243 North Christiana Ave., Chicago, Illinois) when on missionary service in Alaska. It is a flat-land, open-land vehicle--a coupé on ski (see Figs. 11-A and 11-B).

"There is no limit," writes Mr. HANSON, "to the speed which can be attained with this sled providing the terrain is smooth and the snow is not sticky. Soft wet snow sticks to the metal skis and makes the going hard. I have attained a speed of 80 miles per hour in previous models. This latest model--it is now in White Mountain, Alaska--would be capable of even greater speeds. However, due to the usual rough terrain in Alaska, the average speed would be about 50 miles per hour. The sled is built of hickory, spruce, and marine-glued plywood and is so designed with side-thrust springs and constructed that it can stand up under very rough and bumpy going. In other words it is flexible rather than rigid. This model was designed for the relatively level country of northern Alaska and for warmth and comfort in traveling in very cold weather. For work in the mountains a much lighter sled could be designed to carry one or even two passengers (enclosed) and work out quite effectively."

The superiority of this sled on the Arctic tundra to the sturdy yet slow dog-teams for rapid travel is obvious.

Readjustment of credit--The picture of the Ford coupé converted into a caterpillar tractor previously published in the Transactions [p. 425, Fig. 6, 1942] should be credited to Fred Paget of the California Cooperative Snow-Surveys, who took the picture at the end of its route at Soda Springs.

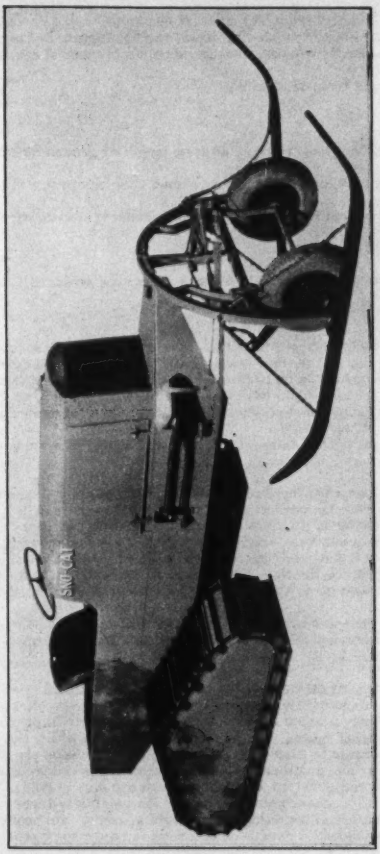

Fig. 10--Tucker Sno-Cat; wheels are drawn up except when lowered for traversing snow-bare areas (Photograph by Tucker Snow Motor-Sled Company)

Needs and problems-- The need of snow-transport is wide and urgent but the local difficulties are varied. The following letters provide a cross-section of the problem:

Hetch Hetchy Water Supply, Power and Utilities Engineering Bureau, City and County of San Francisco, Public Utilities Commission (letter of January 19, 1944, from THORNTON EASLER, Electrical Engineer, in charge of maintenance and operation, at Moccasin, California)--"Our men in the Hetch Hetchy Water and Power Department who are directly concerned with snow-conditions are very much interested in sleds. Our work where we encounter snow is on the western slope of the Sierras from elevation 6,700 down to approximately 3,000 feet. The snow will vary in depth from a foot or two with a heavy moisture-content at the lower elevation to six or seven feet at the

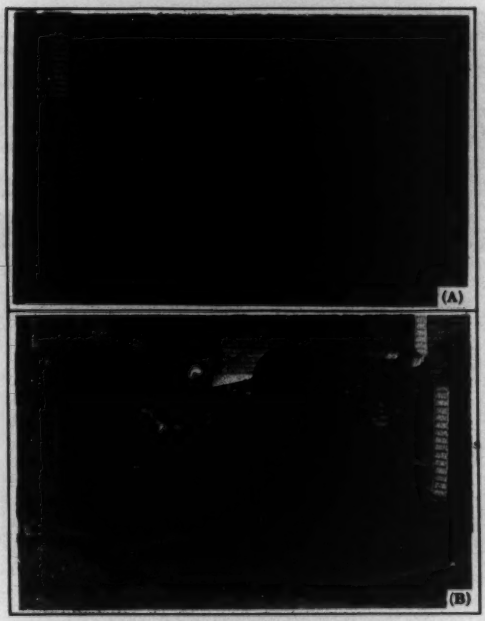

Fig. 11--Alaska air-sled: (A) Front view; (B) side view (note spring to eliminate side-thrust) (Photographs by Ralph P. Hanson)

higher elevation where it may be dry and powdery. The routes we have to travel are open roads in some cases and rough narrow trails in others. These variable conditions tend to complicate the problem of transporation or travel and it is not likely that any equipment would be able to meet all of them unless possibly, as you point out, ultimately the helicopter. However, we may be able to get something that will be of material assistance."

Department of Rural Engineering, Montana State College, Agricultural Experiment Station, Bozeman, Idaho (letter of February 2, 1944, from O. W. MONSON)--"This morning I received some photographs of a new type of Sno-Mobile (see Fig. 12) and also various correspondence concerning this machine. I note that the pictures also include photographs of a snow-mobile designed and built by Dean CLYDE at Logan, which has successfully operated over a total of 1,200 miles [Trans. Amer. Geophys. Union, Part I, pp. 166-176, 1944].

"Our experience with Sno-Mobiles here at Bozeman has been mostly negative. Our snow-conditions are very difficult here and very hard to handle. During the early part of the season, the snow is very loose and powdery and will not stand any weight. For example, yesterday and the day before I made a trip to the Mystic Lake Snow-Courses about ten miles up in the mountains and while the snow was only around two feet in depth, we found traveling very, very difficult because our skis would sink in from eight to ten inches at each step. Also this loose granular snow is very slippery which makes it practically impossible to travel uphill. Where there is sufficient body in the snow to permit fishtailing, one can make some progress but when the snow is so loose and powdery that one flounders around, it is very exhausting to try to make any progress uphill. I doubt whether any kind of a machine would be able to travel over this kind of snow. We have been thinking here a good deal of the possibilities of using an autogiro or helicopter for winter travel

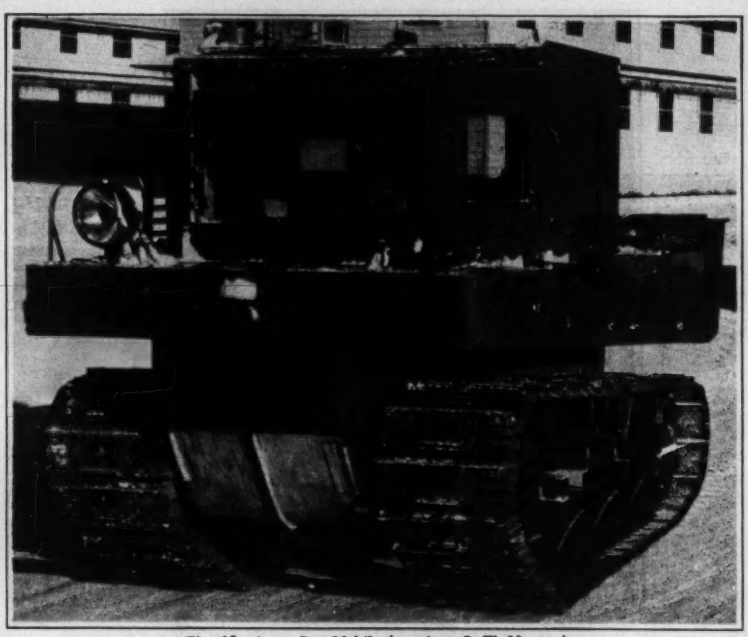

Fig. 12--Army Sno-Mobile (courtesy O. W. Monson)

in the mountains. I believe it would be more practical and perhaps no more expensive. It will be interesting to see what the developments after the war will bring."

Bowater's Newfoundland Pulp and Paper Mills Limited, Deer Lake, Newfoundland (letter dated April 18, 1944, from ERIC HINTON)--"I am very interested in the subject of motor sleds mentioned on page 369 of the Transactions of 1943. We have the problem of servicing 80 miles of high-tension transmission-lines through desolate and in many places uninhabited terrain. The present system of transportation by dog-team is extremely slow and uncertain, sometimes occasioning considerable delay in restoring power-service for the interruptions due to faults in the lines. Although we have not tried the 'Motor-Toboggan', this machine has been used locally by other parties and is reported to be satisfactory except that it is rather too dependent upon the texture of the snow. This confirms the experience of J. C. MARR in Idaho. We are therefore interested in obtaining particulars of the caterpillar type mentioned in the paper already referred to. We would be very grateful if you could kindly give me the addresses of firms manufacturing this and any other type of conveyance that might be suitable for our transmission linesmen."

Transport by helicopter--The inevitability of transport by helicopter is seen in the title 'Greyhound in the sky' in the winter Bulletin of Standard of California, 1943-44, and the statement that 'Greyhound has applied to the Civil Aeronautics Board for a permit to operate, after the war, a nation-wide helicopter transportation-system integrated with Greyhound highway-operations over 49,000 miles of routes. A model of a 14-passenger Air Bus, conceived by the Greyhound Corporation and designed by RAYMOND LOEWY, in collaboration with IGOR SIKORSKY, helicopter inventor, was exhibited at hearings before the Civil Aeronautics Board."

The helicopter seems to be the answer to traversing areas of snow void of landing-fields and perilous with avalanches. The helplessness of the normal plane even on snow-clad lakes is revealed in the epic story of "The Lac O'Conner, veteran of the Arctic snows" under the title "Snow versus aviation" by M. GERSHZOHN of American Airlines Inc. [Bull. Amer. Met. Soc., May, 1944].

Ice on airplanes--The avoidance and control of ice on airplanes is being attacked from every front. A meteorological "Study of ice accretion on aircraft over the Canadian Rockies" by FRANK W. BENUM and HUGH CAMERON of the Meteorological Service of Canada, has been published [Bull. Amer. Met. Soc., January, 1944].

Heat and abrasion are new means of combatting ice. According to Associated Press, the United States Rubber Company has developed a strip of conductive rubber attached to the leading edge of each propeller-blade, through which enough electricity passes to heat the blade sufficiently to keep ice from forming. Dr. LOUIS MARICK of the Company's Detroit Division developed the new anti-icer with the cooperation of the engineering staff at Wright Field. He says [Bull. Amer. Met. Soc., pp. 113-114, March, 1944]: "Anti-icers for warplanes, which shoot hot air through ducts on wing- and tail-surfaces to prevent dangerous ice-formations, have been perfected and are now being installed to make combat flying safer.

"Several advantages are claimed for thermo-anti-icing systems: (1) There is no danger of ice-caking on the wing-surfaces to destroy lifting power. The pneumatically operated rubber de-icers now commonly used are intermittently inflated with air to crack the ice off leading edges, but rough-ice formations are often left on top of the wing which make the plane hard to control. The new thermo-anti-icing system prevents ice from forming anywhere on the surface.

"(2) The device can be operated during combat, at slow flying speeds, and during take-offs and landings, as there is no loss of aerodynamic efficiency in either wing- or tail-surfaces. As better planes required smoother wing-surfaces, the lowered efficiency produced by rubber pneumatic de-icers became increasingly objectionable.

"(3) Destruction of accumulated ice and frost by the anti-icer begins as soon as the engines of the aircraft are started during sub-freezing weather and continues as long as the motors run [Sci. Serv., August, 1943]."

Also [Bull. Amer. Met. Soc., p. 257, June, 1943] "A novel attack on the life-and-death problem of icing on airplane leading edges is represented in the device on which patent 2,324,303 has been granted to C. J. JOHNSON of Encino, California, assignor to the Lockheed Aircraft Corporation. Present de-icers, the inventor points out, are built on one of two principles: Either the alternating expansion and contraction of a rubber 'boot' along the surfaces involved, or the application of exhaust of engine or other source of heat. Simpler, lighter and less costly, he claims, is his method of installing cylinders along leading edges, in wing-slots and at other critical places. These cylinders are slowly rotated, so that fresh surfaces are constantly being presented, and at the same time the already formed ice and slush are being scraped off against sharp blades [Sci. Serv.]."

Winter sports and military service--Owing to lack of gas and crowded condition of trains and buses, winter sports are on the decline even for relaxation by civilian war-workers. The love of skiing, however, has remained unabated and training in skiing for mountain troops including medical men has become a feature of Army life.

The story of Army doctors on skis is told by ROBERT E. GEIGER, Features Writer of Associated Press, as follows:

Camp Hale, Colorado--Imagine your family doctor as a rugged mountain man in Arctic parka and on skis. If he is young, has a sound constitution and is a good physician or surgeon, that may be exactly where he is today. At Camp Hale, near snow-covered peaks of the Rocky Mountains from whose blizzards even hardy mountain trappers shied, fighting men are taught to battle under Alpine conditions. Mountain medical men are trained to go right beside them. The hardy ones were brought together in a medical outfit capable of going where the going is most difficult. These men have been trained in all the tricks of mountain climbing and Indian lore. They can ski. They have lived for days in sleeping-bags or ice-houses on winter maneuvers in the Colorado Rockies with five feet of snow on the ground and the thermometer at 40 below. Under such conditions blood plasma freezes in two minutes; a surgeon's hands, if ungloved, become numb instantly. They learn to overcome these things.

"Major WARD I. GREGG, gentle, slender surgeon from Cambridge, Massachusetts, took his skis one day and fought his way through snow and sub-zero cold to Dillon, 40 miles away and over the Continental Divide at 11,000 feet. Just for the fun of it. That's the kind of a medical outfit the Army is training to care for its wounded men.

" 'We have borrowed ideas from the American Indian, the Eskimo, and rescue techniques tried out in World War I in the Alps,' says Colonel BERMAN, 'all these and others have been incorporated in our training. The old Indian made his squaw drag the household belongings on a travois (a pole framework) behind a horse. We employ this method of carrying a litter under certain conditions, but use sure-footed mules. We also rig a ski soldier's skis into a toboggan to make a sled-litter. There are many ways of getting a wounded man safely from a mountain battlefield hemmed in by blizzards, cold, and high cliffs.'

"In this age of the airplane it would seem simple to land on the top of a mountain to rescue wounded men. However, the airplane and helicopter haven't proved, at this date, as satisfactory or sure as mules and men for this work. In mountain medicine a doctor has to do the most with the least. Mountain battlefields are isolated and inaccessible. Wounded men have to be moved from the fronts, down cliffs to trails leading to field-stations.

"Ptarmigan Mountain, jutting 12,500 feet into a blizzard, is a huge air-conditioned school room for the mountain medical men. It's 30 below on their practice battleground. One plays injured. The litter-bearers, weaponless, crawl across the snow to him. They carry him on the first stage of the long trip to a field-station. On the side of Ptarmigan is a straight cliff. They rig an aerial train of rope. Carefully they slide the soldier, in his litter, over the face of the cliff, lower him gently. At the bottom mules are waiting. The wounded man's ride in the cacolet is jerky and rough, timed to the mule's cadence. Finally they reach a smoother spot where a toboggan can be used. The litter-bearers, on skis, drag the toboggan to a trail. In a jeep, the man reaches a field-station where doctors are waiting with bottled plasma, medicines, and warmth. It's a rugged life, but most of the doctors love it. They say it's healthy."

Ice in rivers--The following is quoted from Engineering News-Record of April 13, 1944: "When the Coast Guard ice-breaker Fern blew for a landing at St. Paul, Minnesota, the last week in March, it was said to be the earliest spring arrival of a Government boat at that port in more than 50 years. It marked the completion of the toughest ice-breaking job on the Mississippi in many years. Resumption of navigation on the Mississippi relieves the hard-pressed railroads of part of their burden of freight at this time."

And the Montreal Engineering Company, Limited, seeks "more recent publications, or additional information dealing with 'Frazil- and anchor-ice' and the 'Physics of underwater ice'."

Publicity

Snow-course markers--In the present era of wide-ranging travel, the snow-course marker designed to identify snow-survey courses serves also in satisfying sympathetic curiosity.

California protects its snow-course markers by explanatory signs (size 12 by 18 inches and 6 by 6 inches) like the ones on the opposite page, which are near the Beacon Hill Snow-Course at Soda Springs.

Mail labels--To win the immediate attention of the recipient, the snow- and water-supply Bulletins of the Division of Irrigation of the Soil Conservation Service bear on their envelopes such identification as SNOW-REPORT, PRELIMINARY WATER-SUPPLY FORECAST, and the Colorado River Conservation District uses WATER-FORECAST.

Bulletins--In addition to the long-established snow-bulletins are the following more recent ones: Snow-cover surveys by the Eastern Snow-Conference, by United States Weather Bureau; Water-supply forecast for western Colorado, by the Colorado River Water Conservation District; Monthly water-resources, United States and Canada, containing maps of stream-flow in relation to normal (median or mid-value), and Information service, both by the United States Geological Survey.

The value of the last is shown in the following paragraph from its issue of August 11, 1944:

"In the Far West 'the deterioration in stream-flow conditions in the important hydro-power-producing region of Washington and British Columbia, especially in the Columbia River Basin' was the most noteworthy event during the month. 'Deficient stream-flow had been forecast by several agencies from surveys of the winter snow-cover, but subnormal rainfall during the spring and summer has aggravated the deficiency. It now appears that the Columbia River will fall near, if not below, that of 1926, the lowest runoff in a 66-year record'."

STATE OF CALIFORNIA
DEPARTMENT OF PUBLIC WORKS
DIVISION OF WATER RESOURCES
COOPERATIVE SNOW-SURVEYS

SNOW-COURSE MARKER

THE SIGN ABOVE MARKS ONE END OF THE LINE ALONG WHICH THE SNOW-SURVEYORS MAKE THEIR MEASUREMENTS.

YOUR COOPERATION IS REQUESTED IN PRESERVING THESE MARKERS.

THEY ARE NECESSARY TO THE SNOW-SURVEYS.

DIVISION OF WATER RESOURCES

Summary of snow-survey data--A summary of snow-survey measurements in Oregon 1926-40 (1940) and a summary of snow-survey data in Columbia Basin (1942), including all past measurements have been issued by the Division of Irrigation. The Colorado River Water Conservation District, Utah Cooperative Snow-Surveys, and Newfoundland have likewise published (1944) a summary for their areas. To facilitate research in snow-survey problems, the long records in Nevada and California should also be summarized.

Magazines and press--Articles on snow-surveying are few but practical. They are represented in "Snow harvest" by FRANK B. HARPER [Sci. Year Book, Chap. 19, pp. 193-199, 1943] reprinted from Country Gentleman, "Five new snow courses established" [Edison News, February, 1944], "Snow by the weigh", by GRACE KIRKPATRICK [The Seattle Sunday Times, December 19, 1943], and "Snow helps win the war" [Soil Conserv. Serv. photographs reproduced in Figs. 14-A and 14-B, to which has been added Fig. 13].

Scientific and technical periodicals--The output this year constitutes mainly reprints and reviews. Science Museum Library in South Kensington, London, has sought a copy of the Proceedings of the Central Snow Conference [December, 1941], of which only a few copies, preserved by the Nevada Agricultural Experiment Station for postwar distribution, remain.

The Arctic Training Division under command of C. A. K. INNES-TAYLOR, Captain, Air Corps, has requested several copies of The Human Side of Snow: II. Sport and Transport, III. Perennial Snow and Glaciers, IV. Snow Perils and Avalanches, and Meteorological Studies in Greenland: A. Climate and Evaporation in Alpine and Arctic Zones and B. Temperatures of Arctic Soil and Water by the Chairman.

Fig. 13--Taking a snow-sample on Seven-Lakes Snow-Course, Oregon (Soil Conservation Service photograph) [See also Fig. 14-A]

(A)

(B)

Fig. 14--(A) Snow up there: A major part of the West's war-food production depends upon the water-supplying snow-pack of the high mountain watersheds in the Cascades, the Rockies, the Sierras, and other ranges. Despite shortage of manpower and other handicaps, hardy snow-surveyors from cooperating, local, State, and Federal agencies have gone up and measured the snow and its water-content this year as they do every year--in order to help farmers, power-companies, cities, and many others to know how much water they may count upon having this coming summer.

(B) Water down here: "It's the water that counts"--water used to best advantage in irrigating this and other Western States' war-food-production acres. When the final April snow-survey reports are in, men of long experience estimate with surprising accuracy how much water will flow in the West's streams and into its reservoirs. Farmers, ranchers, and orchardists, for example, then can lay their plans accordingly for planting and irrigating in accordance with the forecasts, made on the basis of normal rainfall.

(Soil Conservation Service photographs)

Captain INNES-TAYLOR also writes, "I am very interested in Fuchsine dye for use on snow."

H. J. McLEAN, Construction Superintendent, Montreal Engineering Company, Limited, writes: "In 1940 I received a copy of Bulletin No. 23, 'Sixième Assemblée Générale à Edimbourg', which has been a source of information and assistance to us in the design and operation of hydro-electric power-developments under winter conditions in Canada."

Two reference-works deserve special mention, namely: Technical paper No. 10 of the National Resources Planning Board on "Principal Federal sources of hydrologic data" [May, 1943], especially pages 30-32 on snow; and a "Glossary of hydrologic terms" being prepared by a Joint Committee of scientific organizations on Water Works Terms.

The value of reprints for postwar demands is emphasized by the Royal Meteorological Society in the following note in its Quarterly Journal [p. 213, July, 1943]:

"Conservation of scientific and technical periodicals--In an important pamphlet, 'Salvage or storage', the Association of Special Libraries and Information Bureaux (ASLIB) has directed attention to the very large postwar demands for sets of scientific and technical periodicals to replace those destroyed or damaged in institutions in Great Britain and in enemy-occupied countries. Not only will files for the years of the war be incomplete or entirely missing, but valuable stocks of earlier issues will have vanished. Neutral countries will also have suffered interruptions and losses. At the same time the publishers' stocks from which the demands must be met are also reduced as a result of increased circulations in this country and the stringency of the paper control. Anxiety for the future is increased by the fact that private owners are being persuaded by salvage drives to release their copies for re-pulping.

"The ASLIB pamphlet suggests that learned societies, professional institutions, and research organizations, which do not possess good reserve stocks or cannot disperse these to safeguard them against enemy action, should ask all their members to retain their own copies, in order that those not wanted for permanent filing may be called in after the war to complete the stocks of British and foreign libraries.

"It is suggested that Societies should keep a record of members who undertake to cooperate in this way, so that future stocks can be roughly assessed. Where subscribers cannot, for various reasons, retain the periodicals in their own custody, it is suggested that they should offer the publishing organizations the opportunity of storing the periodicals against future needs. Badly damaged or very dirty copies should be sent for salvage unless the periodical is rare.

"In order to cooperate in this scheme the Society is prepared to maintain a list of those who undertake to retain their copies of the Journal for the purpose indicated above, and will welcome offers from members."

The Western Snow-Conference and the Nevada Agricultural Experiment Station have built up a considerable reserve for similar use. Several packages have already been forwarded on request for reading material through the kindness of the Soviet Embassy at Washington to PETER STAKLE of Latvia, formerly Secretary of the International Commission of Snow, and to KANWAR SAIN, Office of the Superintending Engineer, Lahore, India, for research on snow in the Himalaya. The long delayed delivery of the gift-copy of the volume 'Hydrology' to Dr. OTTO LÜTSCHG, President of the International Association of Scientific Hydrology, awaits clearing of the mail route through France to Switzerland.

Reviews

Forecasting runoff from snow-surveys by R. C. FARROW [Geog. J., v. 100, pp. 206-222, 1942]

Review by J. E. CHURCH, entitled "The soil factor in forecasting runoff by snow-surveys" [Geog. Rev., v. 34, pp. 327-328, 1944]--The growing recognition of the value of snow-surveys is well illustrated by Captain R. C. FARROW'S paper. Captain FARROW deals with several questions, drawing his illustrations from British Columbia; only one point will be considered here, however--the effect of the soil-priming factor. As the writer of this note pointed out a decade ago [Snow-surveying: Its principles and possibilities, Geog. Rev., v. 23,,pp. 529-562, 1933] this is one of the chief problems in the forecasting of stream-flow.

In the semi-arid Okanagan Basin [see British Columbia: A study in topographic control, by GRIFFITH TAYLOR, Geog. Rev., v. 32, pp. 372-402, 1942], where there is a thick mantle of unconsolidated material, the soil-priming factor may be very important. FARROW essays to determine the relationship between pre-snow rainfall and the soil-priming factor: "The rainfalls of suitable precipitation-stations were chosen by trial and error for various autumn periods just preceding permanent snowfall and were compared with the disparity between snow water-content, as obtained

from precipitation-records, and recorded runoff of the Okanagan River. Even with the known inaccuracy of deducing water-content from precipitation-records of snowfall, it was evident that a relationship existed. A correction-curve was then developed from which a coefficient could be obtained each year and applied to snow water-content. This method produced results in several years of forecasts, and as years of snow-survey data are built up to replace the past precipitation-data it is believed that it may provide a reliable correction. Unfortunately, studies were cut short by the war."

Progress in observations made in Nevada indicates that accumulating soil-moisture from the snows or precipitation of previous seasons may be the cause of the discrepancy between the current snow-cover and its associated runoff. The potency of this factor of soil-mantle has been evidenced unmistakably during the past two years in the upper Humboldt Basin, where the stream-flow differs considerably from the snow-cover even when corrected for spring and summer rains.

To quote from the forecast of this stream April 1, 1943: "The extremely high water-table of the present season of 1942-43, although the snow-cover March 1 was only 91.4 per cent of its normal, indicates that the runoff at Palisade will be fully 150 per cent of March-July new normal of 215,000 acre-feet and may be considerably above it."

The final percentage for the season was 200. The soil-mantle, being already water-filled, was unable to absorb its usual proportion of snow-melt and turned it into the channel. Since the water-storage of soils changes slowly and may depend on the cumulative effect of one or more seasons, it should be possible, by the observation of the accumulated precipitation or runoff of previous seasons or by well-measurements, to develop a correction-factor to apply to the snow-cover.

Of interest is the divergence between the Klamath River in the lava fields of southern Oregon and the Sierra streams in shallow beds farther south. Owing to the absorptiveness of the lava, the flow of the Klamath for April to July is only 42.0 per cent of the annual, as compared with 71.2 per cent for the alluvial Humboldt, and is affected by its water-table. A similar relationship is being sought between the snow-cover of Charleston Peak in southern Nevada and the artesian wells near its base.

Hydrology, Physics of the Earth series IX, edited by O. E. MEINZER, Chapter 4 on Snow and snow-surveying and ice, and Chapter 5 on Glaciers, were reviewed by W. V. LEWIS [Quart. J. R. Met. Soc., London, October, 1943]; that review is reprinted below.

This is an outstanding addition to an already noteworthy series of volumes sponsored by the American National Research Council. In recent years the contribution of United States scientists to hydrology has been preeminent, and this volume should therefore be invaluable to those countries which, like our own, have up to the present lagged far behind. This very preeminence, however, might help to account for the fact that some conspicuous European contributions to the subject have been overlooked.

In spite of the number of sub-divisions--30 in all, involving 24 contributors--the arrangement of the subject matter in following the hydrological cycle is clear; only a little repetition is involved, and hardly any real differences of opinion emerge. There are some excursions into border-subjects, particularly into geomorphology when the erosive actions of glaciers and of rivers and the hydrology of limestone and volcanic terranes are discussed. The emphasis, however, is such that the true domain of hydrology is never lost sight of.

Intruded rather surprisingly between the chapters on Evaporation from free-water surfaces and from lakes, by S. T. HARDING, are two excellent detailed chapters on snow and snow-surveying and ice, by J. E. CHURCH, and on Glaciers, by F. E. MATTHES. CHURCH has achieved much success in applying the seasonal percentage of snowfall in one basin to adjacent basins, and so developing a technique of wide-area forecasting which in turn serves as a useful index of subsequent river-floods. He considers that two or three key snow-courses (sampling along straight-line courses through typical areas of mountain slopes and forests) in a basin, if averaged, would indicate the ensuing runoff usually within ten per cent. MATTHES deals mostly with glacier-motion, and treats perhaps a trifle uncritically STREIFF-BECKER'S assertion that in deep basins the lower, more plastic, layers of a glacier move by "extrusion flow" three to eight times as fast as the more rigid surface ice does by "gravity flow". Little mention is made of internal temperatures of glaciers in spite of the great advances in our knowledge made recently by AHLMANN, SELIGMAN, and others, but there is a valuable summary of recent variations of glaciers.

A review by Dr. FRITZ LOEWE of the University of Melbourne, of the Chapter on snow and ice, is contained in his letter of May 2, 1944, and is quoted below.

"Although the general interest is for the time being turned into quite other directions, I still try to keep my interest in snow and ice alive, and hope that after the war, the International Association will experience a vigorous revival. The war must indeed have provided a lot of new information

particularly from Greenland, which I hope will somehow be made generally available. You may perhaps be interested to learn that Dr. KURT WÖLCKEN, who made the seismic observations of the thickness of the ice during the German Expedition to Greenland and later on (1932-33) worked with the Russians on similar problems in Nowaja Semlja, is now in Argentine (Direccion de Meteorologia, Paseo Colon 317, Buenos Aires) and could consequently be contacted.

"I came recently across your contribution on snow and ice to the volume 'Hydrology' which gives a very valuable summary of our knowledge about the subject. May I just touch upon a few minor points on pages 89, 90, 94, and 131? The snow-line in Greenland is, except perhaps on very localized places, much lower than 7,000 feet--on an average on the ice-cap about 4,500 feet. I have given a summary of the altitude on the ice-cap [Gerland's Beitr. Geophysik, v.46]. Along the outer coast the snow-line is everywhere lower than on the ice-cap. The snow-line is not highest at the equator but some distance away from the equator and sinks towards the equator, thus: Southern Bolivia; Ecuador 5,000 meters; Kuenlun 6,000 meters; Ruwenzori 4,500 meters; Carstensz Peak (New Guinea) 4,700 meters. This variation corresponds to that of precipitation. The drifting over of Mawson's Hut in Adelie Land does not seem to indicate any position of the snow-line but merely abnormal accumulation of drift-snow behind an obstacle. The slopes behind the station leading to the ice-cap show even in spring for many miles a surface of bare ice [see MAWSON, Home of the blizzard]. Density-variations of a snow-cover are discussed by KORHONEN [Ann. Acad. Sci. Fenn., Ser. A, v. 26]. The daily temperature-variation in snow is treated by KERÄNEN [Ann. Acad. Sci. Fenn. Ser. A, v. 13]."

Films--Additional illustrative material has become available in a set of lantern slides by GEORGE D. CLYDE on the Utah Snow-Mobile and a color movie film of the Tucker Sno-Cat by WALTER J. HERZ. The United States Signal Corps has prepared a sound film in English entitled "Avalanche", based largely on films from the Swiss Avalanche Commission and the Swiss Army, the former of which has had wide circulation in the United States. The United States Army Pictorial Service now desires to distribute the combined film commercially throughout the world and has loaned to the International Commission of Snow and Glaciers a copy for showing by organizations interested in snow. All films are 16 mm and can be borrowed freely as in the case of earlier films.

Themes of leading interest

Two themes of leading interest represent old problems still new and pressing: (1) Ice-conditions on the Winnipeg River, representative of ice-bound streams; (2) the effect of tree-cutting on runoff, supplemental to the Wagon Wheel Gap Study of 1910-26.

Ice-conditions on the Winnipeg River--This is Water Resources Paper No. 3, Winnipeg River Power and Storage Investigations, by J. T. JOHNSTON, Dominion Water Power Branch, published at Ottawa in 1915. In a country where the prevailing temperature-conditions are as low during the winter season as is the case in Canada, the most careful attention must be given to the proper protection of hydroelectric installations from ice-troubles. This is particularly the case in the Western Provinces east of the Rocky Mountains, throughout the section which is now being rapidly settled, and where hydroelectric development is receiving attention.

The troubles, which have been experienced in the past in connection with the operation of power-undertakings in northern latitudes, were for a long period considered a necessary evil and a prevailing condition beyond hope of permanent remedy and only to be met by the yearly employment of local help in blasting and ice-cutting operation. The fact, however, that certain plants were comparatively free from ice-troubles, while others were practically closed under and following certain temperature-conditions, proved an incentive to a closer study of the actual underlying causes and processes of ice-formation. Many papers have been prepared and books compiled on this interesting subject, the most authoritative being probably that on "Ice formation" by Professor H. T. BARNES, Associate Professor of Physics, McGill University, Montreal.

Following this recent fuller appreciation of the underlying causes of ice-troubles, the construction of hydroelectric undertakings in climates where extreme winter conditions prevail, in such a manner that their successful operation throughout the cold season is assured, has largely become a matter of proper forethought and care in location, layout, and design. The successful and uninterrupted operation of the Point du Bois Plant of the City of Winnipeg on the Winnipeg River, throughout the past three winter seasons, is sufficient assurance that no adverse ice-troubles need be anticipated in connection with the development and operation of the projected sites on the river, providing proper foresight is displayed in their design and construction.

In this report, it is not intended to give any detailed study to the origin of and protection against ice-troubles in hydroelectric development. In view, however, of the conditions which must be encountered in power-plant construction and operation along the Winnipeg River, it is considered advisable that a general synopsis should be given of the troubles to be anticipated and of the measures which have been taken to eliminate the same, in connection with the proposed hydroelectric installations along the river.

It is intended to refer only briefly to the three varieties of ice which affect power-plant construction and operation, that is, sheet-ice, frazil-ice, and anchor-ice, with particular attention to the conditions tending to, and produced by, their respective formation, and which are found and may be anticipated along the Winnipeg River. Reference to the section dealing with the winter temperatures of the Winnipeg Basin will disclose the extreme conditions which maintain and which must be combatted.

What is commonly known as sheet-ice is the ordinary ice-covering of ponds, quiet rivers, and protected waters of all descriptions. In its formation and continuance throughout the winter season it has no direct adverse influence on power-plant operation. On the contrary a broad sheet of ice-cover above a power-station is directly beneficial to its successful operation in that it forms a protective covering which prevents the local formation of frazil- and anchor-ice. Then, at times, adverse influence of sheet-ice in connection with hydroelectric development is of two natures, namely, (1) the pressure exerted on permanent structures, and (2) the combined effects of floods and ice-jams during break-up in the spring.

Much has been written and many divergent views expressed regarding the nature and intensity of ice-pressure as developed in the formation of sheet-ice on lakes and reservoirs. Ice, after its formation, is still subject to expansion and contraction accompanying a rise or fall in temperature. The contraction due to a lower temperature results in cracks throughout the ice-cover. These cracks at once fill with water from below which freezes and renews the continuous ice-sheet. A rise in temperature causes the whole mass to expand with a resulting pressure which must find relief. The extreme limit of pressure would, of course, be found in the crushing strength of ice. Such a condition, however, need not usually be anticipated on the surface of a reservoir or pond. Relief may be found in several ways according to the locality; sloping and shelving shore-lines permit the ice-sheet to slide or push its way beyond the limits of the water-surface. The effects and in fact the actual operation of this action can be frequently observed along the borders of large ponds and lakes where long ridges of gravel, boulders, and masses of rock, frequently of surprising size are formed by the ice-push. Wide expanses of water-surface with abrupt shore-lines preventing the above action find relief from ice-compression by the sheet buckling in the center or possibly by crushing.

The general conditions which tend to endanger permanent structures, such as dams, etc., from ice-thrust, are found in narrow or confined waters, where the ice is confined between the structure on one side and an abruptly vertical shore-line on the other. In such cases there is an undoubted and heavy thrust, acting horizontally against the face of the structure at water-level. A heavy ice-covering freezing solidly to the face of a dam, followed by a lowering of water in the reservoir also produces strains of magnitude and character dependent on the local conditions. A rise in the water-level in cold weather following the conditions produced by the above drop, undoubtedly results in a strong leverage thrusting against the dam.

Among other causes of ice-pressure might be mentioned the action of winds on ice-cover. Ice-thrust and movement from this source are frequently very marked. Conditions seldom lend themselves, however, to the full concentration of such pressure on dams and permanent works--irregular shore-line, islands, etc., usually mitigating the same.

An overflow dam, so long as it acts as such, does not experience the above adverse influence from ice-cover, since, so long as there is sufficient overflow, the ice will not attach to the crest. Non-overflow dams, retaining walls, and embankments will, however, experience ice-thrust in the climatic conditions of the Winnipeg River, where local measures of relief, whether natural or artificial, are not available or applied. Cutting the ice along the face of the dam is frequently resorted to in order to relieve pressure of this nature.

No general hard and fast rule can be laid down fixing a definite ice-thrust which must be anticipated and designed for in dams located in extreme climates. The Board of Experts who were commissioned in 1884 to design the proposed Quaker Bridge Dam on the Croton River in connection with the water supply of New York City, advised that an ice-thrust of 43,000 pounds per lineal foot

at the highest ice-line should be provided for. This recommendation was, however, not adopted in the actual construction of the dam, which was built at a site three miles farther up stream, under the name of the New Croton Dam. The recommendation has, however, been frequently quoted in discussion of safeguarding against ice-thrust. The Wachusett Dam, built in Massachusetts in 1900 to 1906, was designed to withstand an ice-pressure of 47,000 pounds per lineal foot at the highest ice-line. Other ice-thrusts which have been allowed in the design of dams actually built in recent years are: Croton Falls Dam, in the Croton Watershed, 30,000 pounds; Cross River Dam, also in the Croton Watershed, 24,000 pounds; Olive Bridge Dam, New York State, 47,000 pounds; Kensico Dam, New York State, 47,000 pounds.

The above dams were all of the reservoir, non-overflow type, and the variation in ice-pressure allowed was due to variation in local conditions as affecting the use and operation of the reservoirs, and as induced by location.

The proposed dams along the Winnipeg River are of a combined free-spillway and sluice-control type. It is intended, however, that the reaches shall be maintained by sluice-control at regulated level throughout the year, and that the spillway shall come into use only as a safeguarding measure, in caring for sudden or extreme floods. Under these conditions, the ice-cover will attach itself to the crest and face of the dam at pond-level. A thickness of from two to three feet of ice may be counted on the undisturbed reaches of the Winnipeg River, where the ice-cover has not been protected by a snow-covering. In general, the dams will not be subject to extreme adverse ice-thrust conditions. No general rule can, however, be laid down as establishing a uniform safety-factor to be applied to the design of the structures. Local conditions, as affecting each site, can only be studied individually and corresponding precautionary measures adopted. The general question of ice-thrust must, however, be given careful consideration in the design of the proposed power-stations and contingent structures. (An interesting discussion on the question of ice-thrust in relation to the design of dams, is to be found in the Transactions of the American Society of Civil Engineers, v. 75, 1912, wherein are submitted the opinions of several widely known engineers.)

The break-up of the sheet-ice in the spring is frequently the cause of inconvenience and sometimes of disaster in power-plant operation. In a river where large blocks and masses of ice, together with other miscellaneous drift, is carried down, there is always a tendency to form ice jams, with consequent backing up of water until the increasing pressure bursts the obstruction and the whole mass is discharged down stream. Such conditions are the frequent cause of the destruction of bridges, dams, and other obstructions in the natural stream-bed. Jams below the power-station have the adverse effect of raising the tailwater and of possibly flooding out the plant.

The Winnipeg River does not, however, give rise to conditions favorable to the formation of ice-jams. The river, as a whole, consists of large lake-like expanses, with deep water and practically no current, connected to each other by drift-falls or short stretches of rapids. In the spring the ice on these reaches as a rule slowly melts and disappears. Where ice-masses break away and discharge over the falls and rapids they are not generally of sufficient extent to form a jam. The slow rise of the flow also has a tendency to reduce the liability to ice-jam formation, and to assist in the quiet melting and disposal of the ice-cover.

After the construction of the proposed system of hydroelectric plants, the present conditions in this respect will be greatly bettered. Above each site there has been provided a large expanse of pondage, extending frequently many miles up stream, and the finally completed system will transform the river into a series of ponds or lakes, with the falls and rapids totally flooded out. These pondages, both collectively and individually, will do away with any present tendencies which may exist in this direction.

Frazil-ice, or as it is sometimes called, slush-ice, has a much more direct bearing on power-plant operation than has sheet-ice. It is a surface-formed ice, its formation occurring in open channels where a too swiftly flowing current prevents the formation of an ice-cover. While a smooth surface permits the formation of frazil-ice in the form of thin plates, an agitated surface offers much more favorable conditions. This disturbance may be caused by wind-action. It is always present to excess in rapids and falls. The ice itself under these conditions forms in fine needle-like crystals which grow and accumulate with great rapidity when conditions are favorable.

The combination of long periods of intense cold with the disturbed water in the rapids and falls of the Winnipeg River, offers ideal conditions for frazil-ice formation. These conditions are, however, largely counterbalanced by the extensive ice-covered reaches.

Throughout the winter season, vast quantities of frazil are formed in the falls along the river, and are carried down stream and lodged beneath the ice-sheets, which are practically always found below. This condition was very evident in the soundings taken along the lower reach of the river by B. E. NORRISH, an engineer of the Department during the winter of 1909-10, prior to the organization of the survey. Deposits of slush-ice beneath the ice-cover were found below all falls and disturbed stretches of open water. In places these deposits were from 25 to 30 feet in depth, and there is every reason to suppose that greater depths were reached where conditions for formation and accumulation were favorable. The natural result of these conditions was a blocking of the river-channel, with a consequent rise in the water-level above. This condition was particularly observed below the Little du Bonnet Falls, where the accumulations of frazil-ice resulted in a rise of several feet in the tailwater-level. This slow rise continued until the rising head was sufficient to clear out the accumulations and to open an under-ice channel, and permit normal flow-conditions to resume, after which the gradual choking up would again commence. Under-ice deposits of the above nature were met from a quarter to half a mile below the various falls.

That this frazil-ice may prove extremely detrimental to satisfactory plant-operation, is illustrated in the Pinawa Channel of the Winnipeg River, where in certain reaches, a narrow and winding channel with rapid current, prevents ice-cover forming, and is particularly favorable to the production of frazil-ice during periods of extreme cold. The deposition and accumulation of these frazil-crystals on the under surface of the sheet-ice in the quieter reaches, at times assumes large proportions and frequently partially blocks the river-channel, necessitating constant vigilance and frequent resource to blasting operations in order to clear both the approach to and the discharge from the power-station.

Although the two terms, anchor-ice and frazil-ice, are frequently used indiscriminately, the two varieties are entirely distinct in source, although in some respects they may after formation, possess somewhat similar characteristics. Differing from frazil-ice, which is surface-formed, anchor-ice has its origin and growth on the stream or river-bed. While turbulent water and low temperature always favor the formation of frazil-crystals irrespective of other conditions, a smooth water-surface exposed to a clear sky combined with low temperature, forms the ideal conditions for the formation of anchor-ice. From Professor BARNES' comprehensive work on the subject, it is apparent that radiation is the prime cause of anchor-ice formation. A clear calm night with little or no air-currents is particularly conducive to radiation, and on such nights the formation of anchor-ice goes on rapidly. A cloudy night is never accompanied by anchor-ice formation. A bridge cover will prevent ice forming in the river-bed beneath, whereas on the same night on the stream above and below, large masses accumulate. Sunshine and a clear sky counteract radiation by day and not only prevent new anchor-ice forming, but loosen the masses previously formed, causing them to rise to the surface, often carrying with them boulders of surprising size. In short, anything which is conducive to the radiation of heat from the river-bed to the colder air above, will tend to the formation of anchor-ice, while anything which interferes with or cuts off such radiation immediately stops or tends to stop its formation.

The ice is granular in structure and forms on the surface of rocks and boulders on the river-bottom, although seldom at a depth exceeding 30 to 40 feet. Frazil-ice after depositing on submerged structures, or on masses of anchor-ice, becomes for all practical purposes of the same nature, and it is this circumstance which leads to the common confusion of the terms.

The effects of frazil- and anchor-ice on power-plant operation

Where conditions are favorable to the formation of frazil-crystals, the question of power-station operation must receive careful consideration. Frazil is a much greater menace to the successful winter operation than is anchor-ice. The crystals attach themselves most readily to heat-conducting structures. One of the most vulnerable parts of a station in this regard are racks. Here the metal, more especially where it projects above the water-surface into the cold outside air, forms a ready surface for the accumulation of ice-crystals, with a consequent partial or complete closing off of the water from the turbines. This is, at times, accompanied by the collapse of the racks due to the pressure of the headwater. The gates are also objects of attack, as are also the wheels themselves. The accumulation of ice-masses in the wheel-pit has frequently been the cause of the complete blocking of the turbines and the consequent closing down of the plant.

Various remedies have been applied to combat conditions of the above nature. These remedies have as their basis the application of heat to the parts affected, that is, to the racks, gates, and turbines. The success which has followed such experiments is founded on the fact that a raising of the temperature of the racks and parts affected by even 0.°001, will prevent the initial attaching of the ice-crystals and their consequent accumulation.

In the layout of new plants, however, in localities where the winter conditions are such that frazil- and anchor-ice are to be anticipated, forethought in the design can largely mitigate and frequently entirely prevent, ice-troubles. In the layouts of the proposed plants along the Winnipeg River, care has been taken to provide conditions in all respects unfavorable to the formation of either frazil- or anchor-ice. At all plants, the extensive pond provided, will form an ice-sheet sufficiently extensive not only to prevent the formation of the ice in question but also to assist to accumulate on its under surface, any frazil which may be formed in undeveloped rapids or falls above. In general, the wheels draw their water direct and undisturbed from the pond without an intervening headrace, and where such has been necessary, easy curves and ample sections have been provided in order that a quiet and undisturbed current may reach the racks. The ice-cover will in all cases practically reach to the protecting curtain along the face of the racks.

Under these conditions, no ice-troubles need be anticipated. This is abundantly proven by the successful winter operation of the municipal plant of the City of Winnipeg at Point du Bois on the same river. No ice-troubles of any description have been experienced here during the three winters in which the plant has been in operation. [For a full and complete study of the question of ice-formation, the reader is referred to the book on "Ice formation" by HOWARD T. BARNES, Associate Professor of Physics, McGill University, Montreal.]

Influence of timber-cutting on water available for stream-flow from a mature lodgepole-pine forest--The following material is from pages 27-30 of the Annual Report of the Rocky Mountain Forest and Range Experiment Station, 1943, by C. A. CONNAUGHTON, Director. From a summation of all various factors of net snowfall and rainfall, we find that, on the average, 16.77 inches of water passed through the forest-canopy on the uncut plots, and 21.78 inches on the clear-cut areas--an increase of 30 per cent in net precipitation as a result of heavy cutting. The lighter cuttings gave smaller gains, varying with the intensity of cutting.

Other moisture-losses--evaporation from the snow and summer evaporation from the soil--also exhibit trends varying with the degree of cutting, but the effects of cutting are not nearly as strong as where net precipitation is concerned.

In order to obtain a final estimate of water available for stream-flow all interception- and evaporation-losses can be combined and deducted from the total precipitation. Following this procedure the results show that, in the aggregate, 10.63 inches of water was available for stream-flow from the uncut forest, or about 43 per cent of the total annual precipitation. The corresponding quantity for the clear-cut plots was 13.88 inches, or 57 per cent of the annual precipitation--an increase of 31 per cent in water available for stream-flow following the heaviest cutting. For the intermediate cuttings, gains in water available for stream-flow were less than for the clear-cut areas but generally proportionate to the amount of timber removed.

From these results we conclude that, at least for this area, managed timber-cutting in mature lodgepole-pine is decidedly beneficial from the standpoint of water available for stream-flow.

As to effects of timber-cutting on the soil, up to the autumn of 1943--three years after timber-cutting--no visible erosion has occurred on any of the plots. Some new seedlings of lodgepole-pine have appeared on the cut-over areas, but otherwise the surface-aspect of the plots has altered very little. The carpet of forest-litter has apparently not changed in condition or appearance, and there has been little or no sprouting of aspen or invasion by grasses, weeds, or weedy plants.

The discussion of these experiments shows that timber-cutting has exerted a pronounced immediate effect on the amount of water available for stream-flow and that, after three years, the treatments employed have done no visible damage to the soil. The effects on water-yield may diminish over a period of years, due to regrowth of the forest or invasion of subordinate vegetation. Also, it is possible that progressive deterioration of soil-conditions may result. Such changing influences can be measured only by repeated observation of the plots; remeasurement of all pertinent factors will be undertaken at intervals of about ten years.

As the immediate effects of timber-cutting on actual water-yields could not be measured quantitatively on the plots, a supplemental study has been started to apply the results obtained on the plots to controlled watersheds and thereby evaluate the effects of forest-treatment on actual stream-flow. The final results of the watershed-studies will require at least another decade for completion. In the meantime, however, results on the plot are strongly supported by those obtained in an earlier watershed-study which was conducted at Wagon Wheel Gap in southern Colorado [see C. G. BATES and A. J. HENRY, Forest and stream-flow experiment at Wagon Wheel Gap, Colorado, Mon. Weath. Rev., Suppl. No. 30, 1928].

In this early investigation stream-flow from two watersheds, each slightly larger than 200 acres, was measured for a period of eight years; then one was denuded by removing practically all woody vegetation, after which the records of precipitation, stream-flow, and other factors were continued for another seven years. The effects of this seemingly severe treatment were not very pronounced, perhaps because both watersheds were rather thinly forested with aspen, Douglas fir, and spruce before treatment, and because the aspen sprouted after "denudation" and rapidly restored the cover. Even so, the results of this study conform so well to the results of our more recent study that it seems worth while to present the following most pertinent comparisons in this report (see Table 6).

Table 6--Comparison of Fraser Experimental Forest results with those of the Wagon Wheel Gap experiment (both expressed only for the first three years after treatment)

Factor	Fraser	Wagon Wheel Gap
Total annual water-yield	Water available for stream-flow increased 31 per cent by heavy timber-cutting	Water-yield increased 17 per cent by removal of all timber cover
Yield during the spring flood	Water available from snow increased 31 per cent	Water-yield increased 24 per cent
Erosion-rates	No erosion visible on the plots	Average erosion from treated watershed 1.3 cubic yard per year
Source of water-losses	Largely interception by forest-canopy; other losses add up to approximately equal quantities for each treatment	Same as Fraser results

Over the whole seven-year period after denudation of the Wagon Wheel Gap Watershed, the increase in annual water yield averaged 15 per cent, while the yield from the spring flood increased about 22 per cent. Erosion-rates remained practically unchanged. The decrease in improvement of water-yields during the seven-year period may be partly explained by the rapid restoration of the forest-cover owing to regrowth of the cut-over stand of aspen.

The conclusions drawn from these experiments and those at Wagon Wheel Gap have shown that timber-cutting in the central Rocky Mountains has a real and immediate influence on the amount of water available for stream-flow from forested watershed-lands. The duration of this effect and its quantitative influence on water-yields in the lodgepole-pine type are as yet undetermined. In this type, however, the pronounced reduction in cover-density by heavy timber-cutting should be expected to cause greater increases than those observed at Wagon Wheel Gap. And, unless cut-over areas are invaded by quick-growing aspen, the return to normal canopy-densities and interception-rates should be relatively slow.

In the lodgepole-pine zone, erosion and floods present a relatively slight hazard, unless unusual damage is done to the watershed by destructive cutting practices or fire.

The results of these experiments cannot be construed to permit devastation of forests in the guise of watershed-management; but they do show that water available for stream-flow may be substantially increased by properly managed timber-cutting. In any area which is sensitive to erosion or susceptible to floods, increases in water-supply from timber-cutting may be more than offset by siltation and flood-damage to both the watershed and water-using areas. In such watersheds

water-production must be subordinated to watershed-protection; and on any watershed the dictates of wise land-management require that timber-cutting must be done only with adequate precautions to conserve all watershed-resources.

Honors, tributes, and appreciation

GERARD H. MATTHES, twin brother of FRANÇOIS and member of the Committee on Snow, has received honorary membership in the American Society of Civil Engineers. Engineering News-Record (January 27, 1944) states: "In 1932 Mr. MATTHES was appointed principal engineer of the Mississippi River Commission, Vicksburg, in which work he made notable contributions to flood-control in the Mississippi. He is now head of the United States Waterways Experiment Station at Vicksburg."

JOHN C. STEVENS, Chairman of the North Pacific Regional Area of the Section of Hydrology, American Geophysical Union, has been nominated as President of the American Society of Civil Engineers for 1945. He planned and supervised the power-installations on the Ebro, Spain, and is the creator of river- and precipitation-recorders, some adapted to report their record by radio.

ERDMAN B. DEBLER, member of the Committee on Snow and Director of the Branch of Project Planning of the Bureau of Reclamation, has been appointed Director of new Region 7 of the Bureau, embracing trans-Rocky Mountains diversion-projects. He had long been Chief Hydraulic Engineer in charge of planning.

The Committee on Snow during the past year has lost the presence and service of PAUL L. BEAN, SALVATORE PAGLIUCA, and J. H. RYAN, all active contributors to the Report of the Committee.

PAUL BEAN has been mentioned under "Memories".

SALVATORE PAGLIUCA, endearingly called "Sal Hepatica", came from Italy in recent years and entered enthusiastically into studies of mountain weather on Mount Washington and at Blue Hill. He entered the war service of his adopted country and lost his life by accident on Mount Mitchell, highest of the Appalachians.

J. H. RYAN was Assistant State Engineer of Oregon and long in charge of snow-surveys, established by GAIL A. HATHAWAY, now Head Engineer, Office of the Chief of Engineers, United States War Department.

Deserving appreciation as a scientist in snow is ALBERT PEPPLER, among the earliest observers at Zugspitze Observatory, highest peak and observatory of the German Alps, and student of snow-cover climatology of Sweden and of the Black Forest in the interests of skiing.

Finally, the unknown men who toil faithfully and alone in the snow-surveys, are represented by MARTIN BROWN on the little Humboldt, Nevada.

The Nevada Agricultural Experiment Station continues to be the physical and spiritual patron of the Committee on Snow and pioneer in snow-studies, thus placing the personnel of the Committee under high obligation.

APPENDIX A--ADDRESSES OF PERSONNEL OF COMMITTEE ON SNOW

Officers

Dr. J. E. Church (Chairman), Meteorologist, Nevada Agricultural Experiment Station, University of Nevada, Reno, Nevada
W. U. Garstka (Vice-Chairman), Michigan State College, East Lansing, Michigan
Captain R. C. Farrow, 1 Calibration Troop, R. C. A. overseas (Hydraulic Engineer, Water Rights Branch, Department of Lands, Victoria, British Columbia, Canada)
Lieutenant Colonel Carl H. Elges, Nevada Agricultural Experiment Station, University of Nevada, Reno, Nevada

Water-supplies

W. W. McLaughlin, Chief, Division of Irrigation, Soil Conservation Service, Box 180, Berkeley, California
L. K. Sherman, Consulting Engineer, 53 West Jackson Boulevard, Chicago, Illinois

R. K. Barrows, Professor Emeritus of Hydraulic Engineering, Massachusetts Institute of Technology, Boston, Massachusetts

Evaporation

Joseph Kittredge, Jr., Professor of Forestry, University of California, Berkeley, California
Francois E. Matthews, Senior Geologist, United States Geological Survey, Washington 25, D. C.

Floods

Merrill Bernard, Hydrologic Director, United States Weather Bureau, Washington 25, D. C.
G. A. Hathaway, Head Engineer, Office of the Chief of Engineers, War Department, Washington 25, D. C.
Gerard H. Matthes, Member of Mississippi River Commission, Vicksburg, Mississippi

Snow-cover and physics of snow and ice

Lieutenant Colonel Bestor Robinson, Q.M.C. Assistant, Office of the Quartermaster General, War Department, Washington 25, D. C.
Dr. Henry I. Baldwin, Forest Research, State of New Hampshire, Hillsboro, New Hampshire
Dr. Howard T. Barnes, Professor Emeritus of Physics, Queen City Park, via Burlington, Vermont
Dr. Phil E. Church, University of Washington, Seattle, Washington
Robert G. Stone, Research Associate, Department of Meteorology, New York University, University Heights, New York
Dr. Ralph L. Belknap, University of Michigan, Ann Arbor, Michigan
Walter T. Wilson, United States Weather Bureau, RFD No. 2, Rockville, Maryland
Ray K. Linsley, Jr., Assistant Hydrologic Director, United States Weather Bureau, Washington, D. C.
Dr. R. W. Gerdel, Associate Physicist, United States Weather Bureau, Sacramento, California

Transport

J. D. MacVicar, Department of Highways, Olympia, Washington
Lacey V. Murrow, Department of Highways, Olympia, Washington

Regional representatives

E. S. Cullings, Secretary, Black River Regulating District, Watertown, New York
Lieutenant Colonel D. B. Freeman, United States Engineer Office, P. O. Box 1216, Omaha 1, Nebraska
James C. Marr, Irrigation Engineer, Box 835, United States Soil Conservation Service, Boise, Idaho
E. B. Debler, Regional Director, United States Reclamation Service, Denver, Colorado
Harlowe M. Stafford, District Engineer, United States Geological Survey, Los Angeles, California
Dean George D. Clyde, College of Engineering, Utah State Agricultural College, Logan, Utah
H. P. Boardman, Professor Emeritus of Civil Engineering, University of Nevada, Reno, Nevada
Fred H. Paget, Associate Hydraulic Engineer, Department of Public Works, Division of Water Resources, Sacramento, California
Chester A. Cummings, Assistant State Engineer, in charge Oregon State Snow Surveys, Salem, Oregon
E. H. Collins, Assistant Chief Engineer, Washington Water Power Company, Spokane, Washington
R. A. Work, Research Project Supervisor, Division of Irrigation, United States Soil Conservation Service, Medford, Oregon.
Eric Hinton, Engineer, International Power and Paper Company of Newfoundland, Deer Lake, Newfoundland
Matthew Balls, The Shawinigan Water and Power Company, Montreal, Canada
O. H. Hoover, Engineer-in-charge, Dominion Water and Power Bureau, Calgary, Alberta, Canada
Dr. William H. Hobbs, Professor Emeritus of Geology, University of Michigan, Ann Arbor, Michigan
Dr. Laurence M. Gould, Professor of Geology and Geography, Carleton College, Northfield, Minnesota

Nevada Agricultural Experiment Station.
Reno, Nevada, October 20, 1944

APPENDIX B--LIST OF CURRENT PUBLICATIONS ON SNOW AND ICE

H. P. Boardman and Ralph W. Burhoe

SNOW

(1) General

COLTON F. BARROWS, Weather fights and works for man, Nation. Geog. Mag., v. 84, pp. 641-670, December, 1943.

MERRILL BERNARD, Hydrology's part in the war effort, Trans. Amer. Geophys. Union, Part III, pp. 7-8, 1943.

J. E. CHURCH, Report of Committee on Snow, Trans. Amer. Geophys. Union, Part II, pp. 341-382, 1943 (includes Appendix A, Addresses of personnel of Committee on Snow, pp. 382-383, and Appendix B, List of current publications on snow and ice, pp. 384-388).

J. E. CHURCH, Snow-study at Soda Springs near Donner Summit of Central Sierra Nevada, Trans. Amer. Geophys. Union, Part III, pp. 77-90, 1943.

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J. CURRANS, How we use snow in art, School Arts, March, 1943.

H. M. DAVIS, Miracle of snow, New York Times, January, 1942.

D. FEATHERSTONHAUGH, Snow rings, Nat. Hist., February, 1942, and discussion, April, 1942.

M. GERSHZOHN, Snow vs. aviation, Bull. Amer. Met. Soc., v. 25, pp. 209-212, 1944.

M. C. GRAMLICH, Sparkling snow pictures, Pop. Sci., January, 1943.

R. F. GRIGGS, Indications as to climatic changes from the timberline of Mt. Washington, Bib. Sci., May 22, 1942.

N. W. HARKNESS, Snow pictures, Nature, January, 1942.

E. L. HAWKE, Thermal characteristics of a Herfordshire frost-hollow, Quart. J. R. Met. Soc., v. 70, pp. 23-48, 1944.

B. HECHT, Snow storm reverie, Readers Digest, January, 1942.

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A. J. LOCKREY, Snow movies, Amer. Photog., March, 1942.

JAMES C. MARR, An Army Air Corps crew saved by finding a snow-survey shelter-cabin, Trans. Amer. Geophys. Union, Addendum to Part III, pp. A-1-A2, 1943.

D. B. MARSH, Eskimo girl builds a snow-house, Nat. Hist., January, 1943.

W. E. K. MIDDLETON, The colours of snowfields in sunlight, R. Soc. Canada, Trans., Sect. 3, pp. 39-43, 1943.

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V. J. SCHAEFER, Fossilizing snowflakes as a hobby, Sci. Dig., March, 1942.

V. J. SCHAEFER, How to fingerprint a snowstorm, Nat. Hist., January, 1943.

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J. C. STEVENS, Hydrology's part in the war effort, Trans. Amer. Geophys. Union, Part III, pp. 5-7, 1943.

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F. THONE, Snow, one of the important ingredients of victory, Sci. Supp., February 5, 1943.

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(2) Precipitation and evaporation

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(3) Snow-surveying

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(4) Forecasting

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(7) Floods

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(8) Conservation

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R. ROBINSON and R. E. TEEGARDEN, Cold weather problems: Last winter and next, Roads and Streets, August, September, and October, 1943.

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Salt proves snow bane, Nation's Bus., December, 1941.

Seven o'clock and all is clear, Binghamton, New York, Amer. City, February, 1944.

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ICE

(1) General

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H. C. TATE, Skate in your own back yard, Amer. Home, November, 1943.

J. D. TWIGGS, Augusta, Georgia, lowers 30 inch cast iron water main by melting blocks of ice, Refrig. Eng., January, 1943.

D. O. WOODBURY, Anesthesia by ice pack, Collier's, October 23, 1943.

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(2) Sea and river ice

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(3) Glaciers

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E. H. COLBERT, Ice age winter resort, Nat. Hist., June, 1942.

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PHYSICS OF SNOW AND ICE

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REPORT OF COMMITTEE ON DYNAMICS OF STREAMS, 1943-44

L. G. Straub, Chairman

The demands of the present emergency upon the members of the Committee have prohibited preparation of a report for 1943-44.

350 Fifth Avenue,
New York 1, New York

ADDENDUM TO REPORT OF COMMITTEE ON LAKES

SUMMARY - GREAT SALT LAKE STUDIES

Ralf R. Woolley

In response to request, the following resumé of current study of Great Salt Lake has been submitted for the Report of the Committee on Lakes.

To date my studies of Great Salt Lake have included the collection and analysis of all available records of fluctuations in lake-levels, areal surveys, and lake-soundings. The determination of areas and proximate volumes for different lake-depths have been given some time, also the chronological development of irrigated areas within the lake drainage-basin.

The results of these studies are indicated on a graphic chart entitled "Variations in level and salinity of Great Salt Lake, since 1850" [Civ. Eng., v. 14, No. 8, August 1, 1944].

Further research is contemplated with respect to the long-time trend of the lake-level and its possible relation to trends in runoff of the streams of the Great Basin, and the probable significance of such trends in future water-problems of the region.

[Note: This addendum received too late to be placed with report of Committee on Lakes, (p. 712).]

U. S. Geological Survey,
Washington 25, D. C.

MISCELLANEOUS REPORTS, LETTERS, AND CRITICISMS

REPORT OF PRESIDENT OF THE SECTION OF HYDROLOGY, 1943-44

J. E. Church

Despite the dissipation of civic effort by war, this second year of the fifth administration of the Section of Hydrology finds the Section buoyant and moving steadily toward its goals.

The plan to have a large and widespread Executive-Legislative Committee functioning by correspondence has been successful and has given a broad outlook to deliberations of the Section. Concentration also has been possible through an active minority, sometimes majority, resident near Washington.

Vice-President STRAUB has been called from the country on a scientific mission and Secretary BEIJ has been almost continuously absent on special work. Consequently, the President's report represents the secretarial activities also. In the absence of both the Vice-President and Secretary, Chairman W. G. HOYT of the Research-Committee on Runoff has acted as Washington executive and, in the present illness of L. K. WENZEL, is also carrying the duties of Chairman of the Committee on Publications of the Section.

Recent activities

The recent activities of the Section have been directed toward the development of (1) Regional Areas, (2) Inter-Society Relations, and (3) Citations and Awards for meritorious papers. New Committees on Erosion and on Hydrologic Regions have been authorized. The growth of the Union in membership and financial resources has been fostered.

(1) Regional development and meetings--The four earlier Regional Areas comprising the Western Division have now been increased to a total of 11 and LEROY K. SHERMAN has become Chairman of the General Regional Committee and Liaison-Officer between the Section and the Union. R. A. HERTZLER, Chairman of the Committee on Program and L. K. WENZEL, Chairman of the Committee on Publications are his associates.

The Central Division, which will be divided into four Areas, includes the central part of the United States east of the Continental Divide and west of the east boundaries of Michigan, Indiana, Kentucky, Tennessee, and Mississippi. The Eastern Division includes the remaining States to the east and will comprise three Areas.

Through the creative energy of MERRILL BERNARD, while on detail at Atlanta, the Southeastern and eleventh Area has been organized with M. T. THOMSON as Chairman and is prepared to hold a local meeting soon at Atlanta, Georgia. The meeting at Urbana, Illinois, being planned on underground water-supplies, has been postponed until peace-time activities are quickened.

Despite the abandonment of the Pacific Coast Meeting of the American Association for the Advancement of Science at Corvallis, Oregon, in 1943, the North Pacific Area held its regional meeting as planned with an attendance of 27. And the South Pacific Area after a delay of a year held its meeting at Berkeley in February, with an attendance of 79.

(2) Inter-society relations--A permanent Committee on Inter-Society Relations has been created for the informal discussion of mutual problems. The membership of the Committee will consist of representatives chosen mutually by the Section and the affiliated organizations but having membership in both.

This Committee included originally the Section of Hydrology and the American Society of Agricultural Engineers but by vote of the Executive Committee now includes also the American Meteorological Society, American Society of Civil Engineers, American Waterworks Association, Geological Society of America, and Soil Science Society of America. Approval is being sought from the Executive Committee of the Union.

(3) Citations and awards--A plan of offering citations and awards for meritorious papers especially by the younger members of the Section has been worked out by G. W. MUSGRAVE, R. E. HORTON, and L. K. WENZEL. Neither money nor medals are contemplated, but rather encouragement to young scientists to enter the forum of discussion. Only thus can the Union maintain growth and strength.

Of special interest because of its purpose and its bestowal on two of the members of the Union, is the Collingwood Prize for Juniors awarded only to Junior Members of the American Society of Civil Engineers for papers "describing an engineering work with which the writer has been directly connected, or it shall record investigations contributing to engineering knowledge, some essential part of which was made by the writer, and contain a rational digest of results. Any mathematical treatment shall show immediate adaptability to professional practice. Accuracy of language and excellence of style will be factors in the award."

The award for 1944 was to RAY K. LINSLEY, Jr. and W. C. ACKERMANN for the paper "A method of predicting the runoff from rainfall" [Trans. Amer. Soc. Civ. Eng., v. 107, p. 825, 1942]. Both are Members of the American Geophysical Union and its Section of Hydrology.

Since this is a new policy and of immediate interest to all of the Sections, it is being referred to the Executive Committee of the Union for approval.

New research and program

Extending the work of the older Research-Committees are two new Committees on Erosion and on Hydrologic Regions to study these subjects in their broadest aspects with a view to preparing comprehensive reports that may ultimately become reference works.

W. C. LOWDERMILK President of the Union, has accepted the Chairmanship of the Committee on Erosion and R. E. HORTON the Chairmanship of the Committee on Hydrologic Regions. C. W. THORNTHWAITE has accepted membership on the former Committee, and on the latter Chairman HORTON has chosen C. W. THORNTHWAITE, MERRILL BERNARD, and L. K. WENZEL as colleagues. Atmospheric as well as water-erosion will be studied and the Sections of Meteorology and Oceanography will be represented. Dr. HORTON is charting the elements of precipitation, runoff, and evaporation of the entire United States in 70-mile-square areas.

Round-table discussions of both subjects will be the central feature of the next Annual Meeting.

Work under consideration

The "Glossary of hydrologic terms" carried far toward completion by the Water Committee of the National Resources Committee should be carried forward by cooperative effort. W. G. HOYT, Chairman, THORNDIKE SAVILLE, and B. S. DRANE of the National Resources Planning Board have been designated to direct the work.

A Committee on Equipment or a Sub-Committee on Equipment in each of the Research-Committees would emphasize the necessity of developing equipment equal to the needs of research, for research can be no higher than the data upon which it is based.

New appointments

CARROLL F. MERRIAM of the Pennsylvania Water and Power Company has been appointed representative of the Section on the Special Committee of the Union on Precise Surveys and Maps. He is particularly interested in the mapping of snow-survey courses.

At the request of Chairman W. G. HOYT of the Research-Committee on Runoff, who has generously assumed the burdens of absent officers, R. W. DAVENPORT has been appointed to the Chairmanship, but Mr. HOYT will remain as second. Mr. DAVENPORT had earlier been Chairman of the Committee on Publications and is now being brought back into service.

M. T. THOMSON, District Engineer of the United States Geological Survey at Atlanta, Georgia, has been appointed Regional Chairman of the Southeastern Area.

Membership and maintenance

The increase in membership and building up of a maintenance fund have gone hand in hand. An ultimate membership of 3,000 is being sought. Approximately 2,000 have been elected with large areas in the Central States only meagerly represented. The Special Fund is reaching its goal and will provide support until the goal for membership is attained. This will assure the appointment of an Executive Secretary to carry details for General Secretary FLEMING and the development of the Transactions as a journal of geophysics.

G. W. MUSGRAVE, Chairman of the Committee on Membership of the Union, and WALDO E. SMITH and W. G. HOYT for the Section, have been very successful in their efforts, as has Mr. HOYT in his Chairmanship of the Sub-Committee on Finance of the Section. This Section, being largest, has necessarily accepted largest responsibility in both. (For reports by Mr. SMITH and Mr. HOYT, see pp. 822-823.)

Ideals

The ideals set before the Section are a sustaining membership, an open forum, presentation of papers for those who can not be present in person, thorough discussion, citation of meritorious papers especially by Junior Members upon whom the life of the Union must depend, breadth of vision, and depth of research. The war is on the wane, the arts of peace and human welfare will soon return. The opportunity of the Section is at hand.

CIRCULAR LETTER OF JULY 30, 1944, FROM PRESIDENT CHURCH TO MEMBERS OF THE EXECUTIVE COMMITTEE SECTION OF HYDROLOGY, AMERICAN GEOPHYSICAL UNION

A second year of service has now passed with full acceptance by the American Geophysical Union of the policies discussed and approved by you. It now remains to carry them into effect.

The Executive Committee has suffered through the absence of Vice-President STRAUB abroad and Secretary BEIJ in war-work at home. Chairman HERTZLER of the Committee on Program has been transferred to the Forest Products Laboratory at Madison, Wisconsin, and Chairman WENZEL of the Committee on Publications is only now slowly recovering from a severe operation. W. G. HOYT has generously consented to become Chairman factotum to carry on the various duties at Washington, D. C., and has been assisted by MERRILL BERNARD, who has now returned from Atlanta to Washington, and by G. W. MUSGRAVE, who has directed the successful campaign for the Geophysical Union to increase its Members.

Annual Meeting--This year's Annual Meeting represents two Union achievements. First it was the twenty-fifth anniversary of the founding of the Union, and it brought the happy news that the Special Fund of $30,000 for the coming three years had been obtained. This is a means toward obtaining support. However, even though it is expendable, it deserves to be called the FLEMING Fund because it was built up first from savings by him as General Secretary and then by membership gifts in support of his ideals. The total was slightly over $10,000. The $20,000 additional represents a gift by the Rockefeller Foundation in tribute to the response made by the membership to the appeal for funds.

If a membership of 3,000 can be obtained during the coming three years with annual dues at $5.00, the permanent support of present plans is assured. The campaign to increase the membership becomes, therefore, the next stage in the development of the Union. Chairman MUSGRAVE feels compelled to withdraw from the Committee on Membership of the Union in which he has had unusual success during the past administration, but the Section of Hydrology will still have the full effort of its representative WALDO E. SMITH, who carried on most of the work during the past year for the increase in membership among hydrologists.

Without waiting for the reorganization of the Committee on Membership of the Union, an annual letter is now being prepared for the entire membership of the Section urging that they meet their quota of 29 per cent of the total Members to be obtained. Fortunately the field has been widened by action of the Executive Committee of the Union to include not only citizens of the United States but also those of other countries. The latter, however, will not have the minor privilege of holding office. In the United States, the field includes also the younger men who have even a general interest in geophysics. They are known as Associate Members but have all of the privileges of the others. The detailed requirements for this group are as follows:

"(f) Citizens of the United States of America (a) engaged in researches not directly related to geophysics but who have interest in the work of the Union, (b) graduate students and alumni of approved schools giving courses in geophysics, and (c) young technicians, observers, computers, and others engaged in work bearing on geophysics, elected Associates by the Executive Committee; they shall enjoy the privileges of Members and shall pay the same dues"

The general attendance of 475 at the Annual Meeting in 1943 and 494 at the Meeting of 1944, even though the sessions were local because of difficulties of travel, is assurance that the field of interest is deep as well as broad. It now becomes a matter of personal effort on the part of the present Members to present the value of the Union to their colleagues in science. The Central States are the present blind-spots in membership-distribution but should be fertile fields for the Section of Hydrology.

The Section of Hydrology, through the initiative of O. E. MEINZER, added human touch to the sessions by arranging a public address by Major RAINIER of MONTGOMERY'S staff in Africa in place of the round-table discussion of papers presented at the sessions, and a report on hydrologic regions by Dr. HORTON, who was unable to be present because of a hydrologic conference and illness that prevented long travel. The response of the public was large and enthusiastic because of intense interest in the problem of supplying water to a moving army in the desert. The success of Major RAINIER, the only survivor of six engineers on MONTGOMERY'S staff, indicates on how slender a thread a campaign may rest, and how HITLER'S failure to capture the essential man resulted in his African defeat. The round-table discussion will be renewed at the next Annual Meeting and will include not only a complete discussion of hydrologic regions based on the original report and supplemental studies by a larger Committee now appointed by Dr. HORTON, but also on erosion, which Dr. LOWDERMILK hopes may be the beginning of a volume on the subject. These two themes have very human applications in the study of hydrologic development and in the saving of soil.

Approval by the Union of new plans--Two broad plans discussed by the Executive Committee during the year were referred to the Executive Committee of the Union for approval and were accepted as policies to be adopted by all Sections at will. These were (1) citations for excellence of papers and (2) inter-society relationships, which will be discussed below in greater detail.

Executive Committee Meeting, Washington, D. C., May 30, 1944--The following minutes by Acting Secretary HOYT have probably already reached you but are here included as a matter of record:

Attendance: J. E. CHURCH, MERRILL BERNARD, G. W. MUSGRAVE, O. E. MEINZER (as Past President and also representing L. K. WENZEL), and W. G. HOYT.

It was the consensus of the meeting that M. T. THOMSON, Chairman of the Steering Committee engaged in canvass of the Members of the Union residing in the southeastern States, is to be congratulated for his activities to date, and that, if time permits while he is in Washington, he present a brief verbal report to the Section of Hydrology as a whole.

The Committee on Inter-Society Relationships was discussed and the President advised that he will report steps taken by the Section of Hydrology looking towards the formation of inter-society relations at the Executive Meeting of the Union to be held on June 2, 1944, with a view to obtaining approval of these activities by that Committee.

The subject of awards was discussed and the President advised that at the Executive Meeting of the Union he would attempt to obtain approval of a plan for presentation of an award (non-monetary) to those Members of the Section submitting the best paper for publication in the Transactions. At the same time he advised he would attempt to interest other Sections in similar action. It was the consensus of the meeting that the present Special Committee on Awards should be continued.

The Committee reapproved the appointment of MERRILL BERNARD, C. W. THORNTHWAITE, and L. K. WENZEL on the Special Committee on Hydrologic Regions, of which R. E. HORTON is Chairman.

In view of the fact that on account of other important engagements Dr. HORTON will not be present at the meetings of the Section to present his progress-report of the Special Committee on Hydrologic Regions and his accompanying paper, "Some hydrologic characteristics of the United States: Part I", it was moved and seconded that W. G. HOYT, acting as Chairman of the Committee on Program for Mr. HERTZLER, would read the progress-report at the scheduled time on June 2, 1944, and that in lieu of the round-table discussion on hydrologic regions scheduled for the afternoon of June 2, arrangements would be made to have 20 copies of the report reproduced and sent to the Chairmen of the Research-Committees, the President of the Section of Meteorology, and Messrs. BERNARD, THORNTHWAITE, and WENZEL, as members of the Special Committee, requesting review and preparation of discussion suitable for accompanying the paper in the Transactions of 194

It was pointed out at the meeting that arrangements have been made by Messrs. FLEMING, LOWDERMILK, and MEINZER to utilize part of the time on the afternoon of June 2, scheduled for the round-table discussion, to have an address by Major RAINIER of the British Army relative to his experiences with MONTGOMERY'S Army, more especially his activities in supplying that Army with water.

The President announced that Dr. LOWDERMILK'S report as Chairman of the Special Committee on Erosion would consist largely of a series of colored pictures covering recent operations and experiences in China.

The meeting adjourned at 15 h.

Only one change should be made, namely, Mr. HERTZLER and not Mr. WENZEL is Chairman of the Committee on Program. Mr. HOYT, however, is also acting as Chairman of the Committee on Publications of which Mr. WENZEL, at that time in the hospital and now convalescing, is Chairman.

Fortunately on my trip East I was able to visit Dr. HORTON a full day at Voorheesville and LEROY K. SHERMAN two half-days at Chicago. Thus six of the Executive Committee conferred and agreed unanimously regarding pending policies of the Section.

These policies as worked out by the Executive Committee of the Section and Union are as follows:

Citations--Since the principal objection to prizes and awards was the diversion of effort from the raising of funds for the maintenance of the Union, the Executive Committee of the Union was assured that neither money nor medals were involved and that the Section of Hydrology welcomed the adoption of citations for meritorious papers by all of the Sections. It was further pointed out that the citations were desired for juniors rather than for seniors in order to welcome new writers and yet to foster high standards. It was further suggested that the judges of such papers should be the entire Executive Committee rather than one or two Members who might be highly specialized in their standards. The Committee was unanimous in granting the Executive Committee of the Section the privilege of developing the plan.

The present Committee consisting of G. W. MUSGRAVE, Chairman, R. E. HORTON, and L. K. WENZEL, who inaugurated the plan, should be continued with power to develop the project and report again to the Committee.

Inter-society relationships--The objection to the Committee on Inter-Society Relationships that it would complicate the relationship of the American Geophysical Union with the National Research Council was met with the assurance that it was not affiliation but conference and informal interchange of views that were sought and that similar opportunity should be given the other Sections. The request again was unanimously granted.

By vote the Executive Committee of the Section has now chosen the following organizations with the following representative for each, namely: American Meteorological Society, CHARLES F. BROOKS; American Society of Agricultural Engineers, H. S. RIESBOL; American Society of Civil Engineers, H. H. HORNER; American Waterworks Association, SAMUEL B. MORRIS; Geological Society of America, O. E. MEINZER or M. KING HUBBERT; Soil Science Society of America, L. D. BAVER.

These choices and nominations should be referred to the officers of the respective Societies for suggestions and nominations of other representatives if desired. Do you yourself desire to make further nominations?

Fear has been expressed by some Members of the American Association for the Advancement of Science that the American Geophysical Union is seeking to become the dominant organization in the field of science. It is not believed that this opinion is held by many for at least the Section of Hydrology has long affiliated with the American Association for the Advancement of Science in the holding of most of its Regional Meetings with the exception of those in the South Pacific Area, where meetings are held by preference in the winter instead of midsummer, the usual date of the Pacific Coast Meeting of the Association. Furthermore, the American Geophysical Union is seeking merely to draw together in understanding the organizations that are interested in geophysical science.

Hydrologic regions--Dr. HORTON has nominated C. W. THORNTHWAITE, MERRILL BERNARD, L. K. WENZEL as members of his Committee on Hydrologic Regions, and has agreed provisionally to await full discussion of his report on "Some hydrologic characteristics of the United States: Part I" before publication. To expedite full but prompt discussion, he has prepared 20 copies of tables and charts while the Nevada Agricultural Experiment Station will prepare as many copies of the text, for the use of the Executive Committee, Chairmen of Research-Committees, and others.

An Atlas is ultimately desired. Dr. THORNTHWAITE is preparing charts of the Eastern States based on precipitation, evaporation, and transpiration, with comparison of United States Geological Survey runoff, and Dr. HORTON is charting the entire United States for the same elements of precipitation, runoff, and evaporation for each 2°-quadrangle of latitude and longitude or approximately 70-mile square area.

The August Scientific Monthly contains an article by CLARENCE S. JARVIS on precipitation and streamflow showing the dependence of discharge by rivers on similar factors.

Erosion--The broadest possible study of erosion is contemplated by Dr. LOWDERMILK, and a volume on the subject is in view. The theme is closely allied with that of Hydrologic Regions and can include the rain-forests of the southeast and the desert-canyons of the far southwest. Dr. LOWDERMILK is a crusader with a world vision, and finds hope even for China's restoration from the devastation by erosion that it has suffered. Dr. THORNTHWAITE will be supplemented by other members of the Committee who will represent all phases of the subject.

Hydrologic nomenclature--I find the following letter of appointment dated March 30, 1943, by Vice-President STRAUB, addressed to Messrs. W. G. HOYT, THORNDIKE SAVILLE, and B. S. DRANE:

> "You are appointed a Special Committee on Glossary of Hydrologic Terms in conformance with action of the Executive Committee of the Section of Hydrology, American Geophysical Union. In accordance with the decision of the Executive Committee, you are requested to consider the feasibility and advisability of preparing a glossary of hydrologic terms, to investigate what has been done in the past in this field, and to recommend to the Executive Committee what action should be taken.
>
> "I appreciate your accepting this responsibility and trust that you will find it possible to present a report to the Executive Committee at an early date."

In my letter to the members of the Executive Committee on February 28, 1944, reference is made to a letter by WALDO E. SMITH suggesting that "inasmuch as the American Society of Civil Engineers, American Society of Agricultural Engineers, perhaps the Society for the Promotion of Engineering Education, and other organizations and committees are working on the same subject, I personally would like to see a bit more integration of effort, but I am unable to state how this may be accomplished at the present stage."

This suggestion was accepted but with the statement that the Section of Hydrology would naturally desire to be a contributor and that letters of inquiry would be sent to the organizations named. These letters have never been written. This must, therefore, remain as a part of the work to be done by the President or by the Special Committee if it approves of the plan. The project has been underway for some years by the Committee on Water Resources of the National Resources Planning Board, and Mr. DRANE is still deeply interested in the work. There is opportunity here to urge the completion of the work undertaken by it or formulate a cooperative plan by the various organizations interested. The Committee should be continued. Chairman HOYT, because of his transfer to Land Utilization, will carry with him even a greater interest in this project than before.

Research-Committee on Runoff--Even before his transfer to Land Utilization, Chairman W. G. HOYT of the Research-Committee on Runoff requested the transfer of his Chairmanship to R. W. DAVENPORT in order to increase the number of workers, but has promised to remain on the Committee.

Mr. DAVENPORT for several years was Chairman of the Committee on Publications and is willing to return to active duty as Chairman on Runoff. His nomination is hereby sent you for your approval.

Membership--Great credit should be given to Chairman MUSGRAVE of the Union's Committee on Membership, to WALDO E. SMITH and to W. G. HOYT, all three Members of the Section of Hydrology, for their unremitting efforts to increase the membership of the Union. All have had unusual success. Mr. HOYT directed his attention particularly to the personnel of the United States Geological Survey.

The next three years must be an era of growth in membership to attain self-support. Will it not be possible for the Members of the Executive Committee to canvass the personnel of their own division?

In this connection, Mr. SMITH makes the following important suggestion: "Inasmuch as it is our desire to make membership available to all who have the qualifications, it is largely the responsibility of the individual Members to do their utmost to find these qualified persons and invite them to submit membership applications, and to act as their sponsors. This responsibility is especially great in those areas of low membership."

Regional Meetings--The organization of the southeastern States is a promise of growth in Regional Meetings to be expected in other areas of the United States not yet organized. This unexpected development is the rich fruit of MERRILL BERNARD'S sojourn at Atlanta.

M. T. THOMSON, who accepted the Chairmanship of the Area, attended the Annual Meeting but did not have the opportunity to present the problems and opportunities of his Area to the Section of Hydrology and feared for a time that he might be forced by war's compression to relinquish the Chairmanship entirely. His letter which appears below carries with it an innate enthusiasm but the feeling that he must step aside for another leader:

"I regret very much that I did not get to meet you and talk with you about our proposed Southeastern Section. My time was so taken up with conferences with Mr. PARKER and others in the Geological Survey office that I did not get more than a few minutes at any of the American Geophysical Union meetings.

"It was my intention to present a report to the Executive Committee, outlining the results of our questionnaire and requesting the advice of the Committee before proceeding. On W. G. HOYT'S suggestion, I am now sending you the data which would have constituted my report.

"Of the 97 Members canvassed, 40 replied; all favoring a regional organization with two questioning the appropriateness during war-time.

"Twenty-three favored Atlanta as a meeting place, with not over two favoring any other city. Twenty-nine favored rotating the meeting places from year to year.

"Twenty-four probably could attend a meeting in October this year.

"Nine could present a paper at such a meeting. Three of these would be from Tennessee Valley Authority, two from United States Forest Service, two from United States Geological Survey, one from United States Engineers, and one from North Carolina State College.

"The Steering Committee originally contemplated holding the meeting at the same time as the State Meeting of the Georgia Section, American Society of Civil Engineers. J. F. LUTZ of North Carolina State College also suggested a joint meeting with the Agronomy Research-Committee of the Southern Agricultural Workers Association.

"The returns show sufficient interest to warrant proceeding with organization under normal conditions. In war-time there is a question as to whether we should proceed. It was my hope that the Executive Committee would help us here to decide.

"If it seems desirable to proceed with a Meeting, it is unlikely that I would be able to take an active part in the arrangements. My staff here is not equal to all the work that we have to do so that I could not, in fairness to my job or my co-workers, undertake to arrange for a Meeting. This is a disappointment to me personally as I fully intended to see it through when I agreed to serve as Chairman of the Steering Committee for Mr. BERNARD. Circumstances beyond our control have cut my experienced people in half while reducing the chances of finding even inexperienced replacements. In spite of this handicap, our work is increasing so that now I simply cannot take on any new outside activities.

"So far as I can I will assist any effort that may be made to organize a Southeastern Section for I believe in it. After the war, I could perhaps do a lot to help.

"Meantime I want to express my appreciation for your interest and for that of the other members of the Executive Committee."

With the consent of his superior, GLENN L. PARKER, Chief Hydraulic Engineer of the United States Geological Survey, the following letter was written in reply:

"Time has traveled so fast since the Annual Meeting at Washington, and duties have been so numerous that your letter of June 8, 1944 has waited weeks for answer. I was startled at the lapse of time.

"I hope, therefore, that both Mr. PARKER and MERRILL BERNARD have told you of the results of a conversation I had with the former regarding your essential place as Chairman of the Southeastern Area of the Section of Hydrology. I was looking forward in keen anticipation to having you address the Section on the newest one of our several Regional Areas and only at the closing session did I learn that you had arrived and were present. But in the confusion following adjournment and my talk with Mr. PARKER, you slipped away unmet. I was greatly disappointed not to meet you in person but I was very happy that I obtained Mr. PARKER'S consent to your remaining Chairman of the Regional Area.

"Your report, therefore, is to me a progress and not a final report and indicates the things that can be done with little effort or travel. I suggested to Mr. PARKER that a local meeting be held at Atlanta and the nine papers be presented either by their authors or by a representative and the papers sent to the Editorial Committee as directed by Chairman SHERMAN for publication. Why not plan such a simple meeting for the coming autumn, in October as you suggest?

"Joint meetings can be planned when things are normal again, or you can appoint a local Chairman at the meeting place of the other organizations such as the American Society of Civil Engineers and the Southern Agricultural Workers Association. Because of the extreme difficulty of obtaining even seats on trains or buses, it seems probable that the American Society of Civil Engineers even in its local Sections will hold few if any meetings this year. Its National Meeting has been called off. I can understand this after having sat four days and nights from Chicago to Reno. Ranger SNIDER of the Forest Service went East because of the critical illness of his mother and was glad even to have a seat part time, and slept on a newspaper on the floor of the smoking room. Travel difficulties are, therefore, very real. They should not, however, prevent the holding of strictly local meetings such as yours at Atlanta would be.

"You are starting with a very satisfying membership. You apparently have 40 and when the organization is started will probably receive many of the other 37 who were canvassed but did not reply. The fact that you could probably have 24 in attendance at a meeting places you in a class with the Pacific Northwest where we had only 30 at Corvallis. In our well-established South Pacific Region at Berkeley last February we had not more than 75.

"Can you not, therefore, proceed with your organization, selecting an Executive Committee or Steering Committee as you have called it, to perform the active work? Your work will be to suggest and to bind together various plans and groups rather than to perform the active work. We are all cut down to the lowest but still find that we can carry on better than we had thought. I still, however, feel that I should be three rather than one to complete the work that has now gathered close around me. You doubtless feel the same. Will you not please, therefore, guide your new organization until the close of the war, which now seems to be almost bursting upon us, and then unleash your activity in the development which must follow?"

It is hoped that Chairman THOMSON will continue to hold his membership together until the release of pressure at the close of the war permits him to put himself more fully into the effort.

It is also hoped that the plan of holding a Regional Meeting next October can materialize on a local scale, in order to make available for publication the several papers now ready. Travel will necessarily be restricted, for even the American Society of Civil Engineers has abandoned its summer meeting at the urgent request of the military authorities.

The Regional Meeting planned for Los Angeles next winter will doubtless be held since Southern California is very compact and the distances short. Other Regional Meetings await the close of the war now dawning.

L. K. SHERMAN has consented to act as Chairman of the Committee on Regional Meetings and as liaison officer on Regional Meetings between the Section of Hydrology and the American Geophysical Union. His letters of March 31 to the President and to the Chairmen of Regional Committees and to M. T. THOMSON, particularly, are a blend of news and wisdom. They confirm

the President's feeling that legislation can be carried on by correspondence with much the same vividness as when face to face. His letter to me, dated March 31, 1944, follows:

"Yours of the 23d at hand. I am glad to note that you are getting along so well. I judge you had had quite a close call in your accident on the snow-fields.

"The Transactions of 1943 of the American Geophysical Union have just arrived. The size and quality of Part II on Hydrology compares favorably with any of its predecessors. This is saying a great deal for war times. In Appendix A-3 I find the change in item (7) and also that I am drafted for the Regional liaison job. I will do the best I can until further developments are made.

"The local chapter of the American Society of Civil Engineers meets at St. Louis on April 26. HORNER got HOWARD COOK on the program to present a paper on the procedures of the United States Department of Agriculture on flood-reduction. HERTZLER and I will be there and maybe HORTON.

"I was much pleased with the interest taken in my paper at the Regional Meeting of the South Pacific Area. I am sending Dr. VEIHMEYER a sort of closure or summary of the valuable discussion. This sort of an airing is most valuable in guiding any future work of an author, provided he has sufficient judicial and scientific acumen to follow the facts even when they may controvert his preconceived ideas."

Some criticisms--The following letter to me from Acting Chairman HOYT of the Committee on Program presents constructive criticisms of programs and discussions at the Annual Meeting and furnishes material for Committee discussion during the coming year:

"Having performed most of my pleasant duties in connection with the Twenty-Fifth Annual Meeting of the Union, it now becomes my unpleasant task to transmit the opinion of two prominent Members of the Section with respect to the program of the Section of Hydrology.

"The program this year was not far different from the programs of the last several years. The number of papers was, as usual, large and but little time was afforded either for presentation thereof or for discussion. It is my belief that the Executive Committees should give earnest consideration to the comments attached. They may represent the views of a considerable majority of those who have been attending the meetings of the Section during the past several years."

"I have been attending the Annual Meetings of the American Geophysical Union for a number of years. Every Meeting has left me with a feeling that the arrangements of the program, and the selection and presentation of papers could stand a good deal of improvement. The provision for formal discussions of scheduled papers adopted a couple of years ago is a step forward. It does not, however, go far enough to make the meetings worthwhile.

"It is the purpose of this communication to outline a procedure which may eliminate most of the defects of our Meetings and greatly improve the value of the Transactions and of other publications. The suggested procedure is based on the following premises:

"(1) The American Geophysical Union and the Section of Hydrology within it are dedicated to the discussion of fundamental problems of geophysics and of hydrology.

"(2) The Union and its component Sections and their publications are not intended as a sounding board for anyone who wishes to present a paper which may or may not be related to fundamentals or to methods useful in arriving at fundamentals.

"(3) To be of value the number of papers published annually in the Transactions should be greatly reduced by an adequate process of selection. Papers on related lines within the field of Hydrology should be grouped and a particular subject treated in a group of papers each supplementing the other rather than by several unrelated, unconnected papers.

"(4) For the purpose of presentation and publication of papers the field of Hydrology should be divided along functional lines rather than subject matter (precipitation, runoff, infiltration, etc.) as are the Research-Committees. A logical subdivision would be (a) ground-water, (b) runoff from small drainage-areas including fields and in general drainage-areas on which subsurface runoff constitutes a small part of total runoff, and (c) large drainage-basins. Each of these major subdivisions include most, if not all, of the now recognized subjects such as precipitation, infiltration,

runoff, etc., but is concerned with them in a somewhat different manner.

"(5) The interests of the membership of the Section of Hydrology follow pretty closely the subdivision suggested under (4) above. The Members can and should be logically classified according to their interests.

"(6) Scientific literature in general and that in the field of Hydrology in particular are being cluttered up with so much impertinent and loosely related material that it is becoming increasingly difficult to use.

"(7) The idea of least interference on the part of editorial boards and committees to insure that worthwhile contributions may not be lost is theoretically sound. In practice, however, it results in the cluttering up of the publications and in a greatly lowered scientific prestige of the society or organization behind the publication. Yet the return to the system of rigid control by a small Editorial Committee is neither practical nor desirable. Unless sufficient funds are available to pay for the services of a considerable group of competent reviewers the papers will not receive adequate treatment. Even the best group of selected leaders, paid or unpaid, cannot be competent in all phases of a science which is in its embryonic stage, a stage when few if any laws governing the natural phenomena involved have yet been discovered or definitely established.

"With the above premises the writer suggests the consideration of the following procedure:

"(1) The membership of the Section of Hydrology should be canvassed to determine in which of the three major subdivisions their interest lies. (Note: One or more major subdivisions may be added if deemed necessary.)

"(2) The Committee on Program and Committee on Publications should immediately after each Annual Meeting invite the membership to prepare papers for the next Meeting with a stipulation that brief but adequate abstracts be submitted to them not later than six months before presentation.

"(3) The abstracts of all papers should be grouped by major subdivisions, reproduced, and sent to those identified with the proper subdivision. The recipients of such abstracts should be asked to submit within a month their opinions of the paper and to indicate whether they intend to prepare a discussion or a companion paper on the same subject.

"(4) The Committee on Program and Committee on Publications should examine the comments and replies of the membership and should select for presentation and publication one or possibly two of the papers receiving the greatest number of favorable comments and for which the largest number of discussions will be prepared.

"(5) With the procedure outlined above the program of the Annual Meeting can and should be announced at least a month before the Meeting. The program can be limited to three groups of closely related papers with the contents of the leading paper in each group known to the interested members.

"(6) The Meeting can and should under this procedure be devoted to the discussion (not presentation) of a small number of papers in which most of the Members interested in the subject will participate. Those who are not particularly concerned with one or more of the leading papers can utilize the time to great advantage in attending the meetings of other Sections or in private discussions which are important purposes of Annual Meetings.

"(7) The Committee on Publications should consist of a sufficient number to adequately represent the several major subdivisions. Members of the Committee on Publications should attend the discussion of papers in their field of interest in order to be in a position to judge from the reaction of the group and the contents of the several discussions which of the discussions constitute enough of a contribution to make their publication worthwhile.

"It is the writer's opinion that if the Section of Hydrology of the American Geophysical Union and its publication are to gain the prestige and respect they should have, some such procedure as outlined above or a modification of it will have to be adopted in the very near future."

"We surely must do something before another year to sift out poor papers. Criticism of this year's program is rife and pointed. I believe we all could agree that if we had had the one-third best papers only and more time for each of these, the program would have been better. This is not criticism of any person but of the failure of our system to work. There were a few excellent papers on the program. These, however, were nearly submerged by the indifferent ones and the obviously very weak ones. The authors are getting the idea that all they need to do is submit a title at the last moment and our rules 'be damned'. Perhaps it is not too late to do a little sifting even now, although I realize that is difficult. Should we not lay plans for the ensuing year at an early date?"

Ideals--As a background for your discussion are the following fundamentals: A sustaining membership, an open forum, presentation of papers for those who can not be present in person, thorough discussion, citation of meritorious papers especially by Junior Members upon whom the life of the Union must depend.

A journal of geophysics is now being realized through the evolution of our Transactions with papers at intervals as they are matured for publication, but the name will remain Transactions of the American Geophysical Union.

An Executive Secretary has been authorized but the spirit of the Union and its larger vision will still be embodied in Dr. FLEMING as General Secretary and in the Executive Committee of the Union. F. R. MOULTON, Permanent Secretary of the American Association for the Advancement of Science, is an example of an activating and philosophic leader. His Bulletin is a monthly message to the membership that has changed the American Association from a group of affiliated organizations into a very human membership feeling and thinking as a group.

Election of new officers--The officers of most Sections were elected this year but those of Hydrology will hold over until the next Annual Meeting. It has been usual to select a Committee on Nominations, but in 1942, when the present officers were chosen, suggestions for nominees were requested from a larger group of the Members.

Should not the entire Executive Committee and other electors chosen by it be polled this year and in the future as is done in the American Association for the Advancement of Science, that depends upon a large electorate representative of the entire body? There would thus be less chance for a partisan choice but still sufficient restriction to provide a careful estimate of qualifications. Thus the will and welfare of the entire Membership can be more nearly assured.

Annual letter--An annual letter is being written to the Members of the Section to continue the New Year's Letter of April 7, 1943. Would it not be well to write such letters annually as a means of increasing solidarity?

The "Travel echo" written to the many met on the journey to Washington for the Annual Meeting gives a glimpse of the Section in action.

DISCUSSION

S. W. LOHMAN--I have just received and read with great interest your mimeographed letter of July 30 addressed to members of the Executive Committee, Section of Hydrology, American Geophysical Union, and I appreciate very much your sending me a copy of this very interesting letter. I have a few comments I should like to make.

As regards inter-society relations, there are listed several allied organizations chosen by vote of the Executive Committee. I believe the Society of Economic Geologists should also be strongly considered for possible inclusion among this group of affiliated or related societies, and if there is agreement on this point I would suggest that Dr. MEINZER be asked to nominate a representative. The Section of Hydrology includes a large number of ground-water geologists, many of whom are members of the Society of Economic Geologists, and since practically all the work of these geologists has potential or actual economic importance, they are indeed economic geologists. Moreover, the Society has in recent years encouraged the presentation of ground-water papers at its meetings, so that in one sense it may seem that the publications of the two organizations might overlap somewhat. As a member of the Committee on Membership of the Society of Economic Geologists, I recently had occasion to point out to the Chairman that although there might be some overlap in this respect I feel that ground-water papers of theoretical or quantitative nature rightly belong in the Transactions of American Geophysical Union, but that reports on the geology and ground-water resources of specific geographic areas would find a logical outlet in the Bulletin of the Society of Economic Geologists.

R. A. HERTZLER--Recent correspondence from you, including the minutes of the Executive Committee, call for an answer or opinion on several questions. I approve heartily the nomination of R. W. DAVENPORT to take over HOYT'S duties as Chairman of the Research-Committee on Runoff. HOYT has been a dynamic force in the Section and I hope his energy and vision will be utilized in other, perhaps larger, capacities.

I also approve the inclusion of the Society of Economic Geologists in the membership of the

Committee on Inter-Society Relations. Do you not think it would be a good idea to nominate S. W. LOHMAN as its representative?

Regarding the Committee on Nominations for officers of the Section, I believe your idea of the Executive Committee plus other Members is a good one. I suggest the remainder of the Research-Committee Chairmen, and in addition the Past Presidents (especially Mr. GROVER), and possibly a few influential men with sound judgment. The Chairmen should be appointed by the President. This, I am sure, would give a democratic organization and one with the depth of perception required for a very important assignment.

The problem of the type of program for the future causes me deep concern. In general I share the opinion which you have expressed in one or two of your recent letters, namely, that young scientists should be encouraged to present papers at the meetings of the American Geophysical Union, and I think it would be unwise to destroy this healthy encouragement. I believe that the procedure outlined in the letter transmitted by Mr. HOYT would definitely destroy this incentive and for that reason is contrary to the guiding policy of the Section of Hydrology. Therefore, I cannot accept it. In my opinion there are other objections to this procedure. More specifically, for example, the suggestion that "presentation and publication of papers in the field of hydrology should be divided along functional lines rather than subject matter", in my opinion is a misconception of the functional as against subject matter. Problems in hydrology are not confined to the "functions" as sub-divided under Item (4). The general problem involves all phases of hydrology such as those recognized by the titles of our Research-Committees. These, therefore, are the functional lines, and suggestions such as "large drainage-basins" are really the "subject matter". To me the most logical breakdown in the field of hydrology is just about as it was conceived in setting up Research-Committees. The programs of the Section for this reason have always been arranged by grouping papers under these headings.

I believe further that there is some confusion concerning the duties of the Committees on Publications and on Program. To me it is conceivable that a paper could be presented at the meeting but not included in the Transactions if it is considered unworthy of publication. This puts the responsibility for the Transactions upon the Committee on Publications but in no way improves the quality of the Annual Meetings. It is the latter which concerns me more directly and I should like to do what I can to make the meetings most successful.

With this in mind, I propose writing to the members of the Committee on Program to ask them for suggestions but before I do so I should like to have some additional information. First, I should like to know what machinery has been set up for editing and selecting papers for publication. Secondly, I should like your opinion as to whether the comments received after the last meeting were the feeling of a majority of those Members present or of only a few. With this information and any suggestions that you may have I shall be able to canvass the members of the Committee on Program and perhaps arrive at some procedure for improving the quality of the Annual Meetings.

With the present facilities and organization I do not see much hope for a very great improvement because the Research-Committee Chairmen who are experts in their field are also members of both the Committee on Program and the Committee on Publications, and if this group of men are unable for one reason or another to evaluate the papers and limit the presentation and publication to the most desirable ones, I do not see how they could make a much more critical appraisal of fewer but longer papers. However, I have hopes that a definite improvement can be made under the new arrangements.

In conclusion it is my opinion that the greatest benefit achieved by attending meetings is not the complete grasp of technical details as given in oral presentation but in the associations and fellowship gained at these meetings. One can, however, decide from an oral presentation whether or not he wishes to give the paper more profound study later. I have just one more thought and that is that it would be impossible to arrange the program of the Section of Hydrology so that the papers of particular interest would not be given simultaneously with those of other Sections. It is obvious that a paper of particular interest has different significance for almost every Member of each Section. I hope that you will feel free to give me your ideas on the type of program to be followed in the future.

G. W. MUSGRAVE -- In reply to yours of August 29, I have consulted with several individuals who are Members of the American Geophysical Union and the Society of Economic Geologists. It is the general opinion as far as I can ascertain that representation of the Society of Economic Geologists in your Committee of Inter-Society Relations would be a good thing. Accordingly, I would

vote in favor of Mr. LOHMAN'S recommendation.

I note your comments to Mr. LOHMAN with reference to the quality of papers and of the desirability of including young scientists on our program. Both of these I very much favor and do not believe that there is a conflict in the two ideas. As a matter of fact, it seems to me that if a young scientist presenting a first paper can present one of quality, he then will have already made his great step forward. Probably it is the duty of some of us to help protect him from his own mistakes and to guide him gently and in every way possible help him to achieve quality for his own sake if for none other. Sometime I want to tell you personally of a specific case in which the first paper of a young scientist was not approved in its original form and where further work was recommended on a certain phase of the problem. The author followed the suggestions and in the succeeding year presented a paper which was almost immediately recognized and which put this young worker in a very favorable position for his own progress. Do you not think that all of us owe some measure of help and guidance to these young workers?

ROBERT E. HORTON--Replying to your letter of September 7 stating appointment of Messrs. WILSON of the Weather Bureau and LANGBEIN of the Geological Survey as Sub-Editors, I would say that HOYT'S letter suggests the possibility of three Sub-Editors and I fully concur in this. The Section is seeking to build up its Membership in the engineering profession, outside of Governmental agencies. For various reasons it seems to me that it would be highly desirable to have at least one Sub-Editor representing the engineering profession. The American Water Works Association might, for example, be asked to suggest a man who is a Member both of that Association and of the Section of Hydrology of the American Geophysical Union.

In this connection I will add a line or two regarding suggestion made in a re cent letter that papers be restricted in size and number. For the most part I do not concur in the suggestions made in that letter. Neither do I believe that a paper should be rejected merely because it contains some erroneous or questionable material or conclusions, provided it does contain something which represents an honest-to-goodness individual research and an advance--no matter how trivial--in the science of hydrology. It is almost a necessary incident to research-publication that no paper is ever absolutely final or perfect. Discriminating readers will, however, in general, not be greatly misled, especially if, as I have long advocated, the basic data be published in the paper so that the reader can make his own deductions and draw his own conclusions. In one respect I feel that much of the publication of the American Geophysical Union is superior to publications of some other organizations which more nearly meet the requirements of the objector above referred to, in that most of the papers published do contain original data. This is, of course, a large subject and it cannot be even satisfactorily summarized in a short letter. My own opinion is that with the publication of a journal, papers should be available for submission for publication at any time, without being presented before a meeting, and that one of the primary functions of the Editors of the Section should be to cooperate with the authors of papers, suggesting amendments and revisions which will improve the character and quality of the paper rather than rejecting the paper because of deficiencies, provided it meets the one fundamental specification that it contains something of real value.

GEORGE B. CRESSEY--I have been out of the country and am thus only now reading your newsletter to the Members of the Section of Hydrology of the American Geophysical Union. I indeed appreciate the various items which you have included, but I only wish to comment on one, namely the proposal to increase the dues to $5.00 a year. This I feel would be a mistake as it would result in the loss of a considerable group of people for whom geophysics are peripheral. Many people are willing to pay a fee of $3.00, but I feel that we would defeat our purpose were we to increase it beyond that point.

L. K. SHERMAN--Replying to yours of September 28, I vote "yes" to Chairman LOHMAN'S proposal to include the Society of Economic Geologists. I nominate Mr. LOHMAN as our representative.

In your Annual News-Letter I was pleased to see Captain A. L. SHARP'S interesting account from "somewhere in New Guinea". This gave a vivid picture of things as they are that was better than a whole set of books. SHARP exhibits the spirit of the pioneer and the scientist. He accepts facts and wretched conditions as they are without exploiting his real heroism. Just as you did on your journey West from Chicago, he can laugh at things which would try the soul of Job.

The critical letter, presented through HOYT, in your message to the Executive Committee, is constructive and calls for action by the President and Executive Committee. The critic has given much careful thought to the work and procedures of our Section. I do not agree with the critic on

all points, re the type and quality of papers submitted and printed. The Transactions for 1943, Part II, are with scarcely an exception among the most useful and progressive articles on hydrology yet produced. No censor could improve upon it. Much good work has been done by HERTZLER and others to secure and present valuable discussions.

On the selection of papers for oral presentation, we have commented and made rules but have made no progress. At the Annual Meeting of 1943 practically the entire list appeared on the printed program for presentation orally and there was little or no attempt at abstracts or condensation. Some papers, valuable in print were not at all suited for reading. The program for the first day ran over into the last day. When a writer's paper is on the printed program, the Chairman of the Meeting has to call his paper and not give the time to JONES. All he can do is hold each to his ten minutes and hurry on to the next without comment or opportunity for general discussion. We do not want to curtail contributors or contributions.

I would suggest that next year the program for the Annual Meeting be submitted to the Executive Committee for final approval before printing. If necessary the Session should be three days instead of two, or else two meetings should be held in different rooms simultaneously.

I was pleased to learn that WALDO E. SMITH had accepted the post with the American Geophysical Union. I think that he is an ideal man for that work.

REPORT TO THE SECTION OF HYDROLOGY OF THE MEMBER OF THE COMMITTEE ON MEMBERSHIP FROM THE SECTION OF HYDROLOGY, JUNE 1, 1944

Waldo E. Smith

From April, 1943, to May, 1944, the American Geophysical Union had a gross increase of 306 new members and a net increase in membership of 253. There was a net gain in affiliations in the various sections of 509 of which 199 or 39 per cent were with the Section of Hydrology. In May, 1944, there were 4,382 affiliations with the various sections of which 1272 or 29 per cent were with the Section of Hydrology. Although the growth was slightly less than during the previous year, it was 18.5 per cent for the Section of Hydrology as compared with 13.3 per cent for the Union as a whole.

This slowing down does not indicate that we are near the saturation point, but is perhaps due to the National emergency. A study of the geographic distribution of the membership of the Union as a whole indicates a membership per million inhabitants ranging from 163 in Nevada to zero in South Dakota. Almost all of the States of the Mississippi Valley have a membership of less than ten per million. Most of the Mountain and Pacific States, in which region the membership-level is generally at its highest, have 25 to 50 members per million inhabitants. The membership in the States of the Atlantic Seaboard averages only slightly higher than that of the Mississippi Valley.

Inasmuch as it is our desire to make membership available to all who have the qualifications, it is largely the responsibility of the individual members to do their utmost to find these qualified persons and invite them to submit applications for membership, and to act as their sponsors. This responsibility is especially great in those areas of low membership.

Our Section President is especially to be commended for the outstanding level of membership reached by his State, Nevada, in which development he has fulfilled an important role as an interpreter of the Union and in inviting those qualified to become Members. The example of Dr. CHURCH and his colleagues in Nevada may well be emulated over the country generally. Let each Member shoulder his full share of the responsibility and contact at once his qualified associates and friends in this regard.

WALDO E. SMITH, Member of Committee for Section of Hydrology

REPORT OF SUB-COMMITTEE ON FINANCE

W. G. Hoyt, Chairman

I expect that on June 2, 1944, at the business meeting of the Union, Chairman FIELD of the Committee on Finance of the Union, will present a report for the Committee as a whole. Dr. CHURCH has asked me, however, to give a brief report summarizing the activities of the Section of Hydrology.

Early in November it was very evident that contributions were coming in very slowly in response to the general letter from Dr. FIELD. Sub-Committees on Finance were therefore formed in each Section. As Chairman of the Sub-Committee for the Section of Hydrology, I asked some 60 members of the Section throughout the United States to act as sub-sub-chairmen and furnished each with a list of from 10 to 20 Members who had not contributed. Almost without exception these 60 men accepted their responsibility and as a result some 250 to 300 Members, who had not previously subscribed, made contributions ranging from $1 to $100, with an average of somewhat over $5. Since most members of the Section of Hydrology are also affiliated with other Sections, contributions are split up and credited to other Sections; it is difficult, therefore, to tell just how much of the total actually came from Members of our Section. I do know, however, that as a Section we rank near the top in any breakdown that may be made. Being the largest Section, our total contribution is naturally the largest. On the other hand, on a percentage basis I believe we rank near the top, notwithstanding the fact that no attempt was made to canvass some 300 or more Members who have joined during the past two years and notwithstanding the fact that I believe 90 per cent of the members of the Section are opposed to contributions as such and feel that the annual dues should be raised to $5.

One prominent engineer to whom a list of Members to be contacted was sent has written me some comments under date of November 15, 1943, which are worthy of consideration by the Section's Executive Committee and are therefore quoted below.

"Referring to your letter of November 8 and Dr. FIELD'S request of September 25, I must say that I am not wholly in sympathy with the idea of setting up a paid staff for the American Geophysical Union and the publication of a monthly or bimonthly magazine. It would seem to me that the cost would be out of all proportion to the needs of the Union.

"I can well appreciate the hard work done by Dr. FLEMING and his associates in past years, and it would seem that a single paid assistant, or perhaps two, would be sufficient to meet the needs of the present situation. If a more elaborate organization were set up, the pressure to enlarge it would be more or less continuous. We have all noted the mushroom growth of newer Governmental organizations at Washington during the past few years. It seems to me that this is a time for retrenchment rather than expansion in the activities of scientific societies.

"As to the printing of papers, I have for several years thought that the number of papers read at meetings and printed in the proceedings of the Union is altogether too large. I am of the opinion that a hard-boiled editorial committee could with profit eliminate fully two-thirds of the papers and require some condensation in most of the others. There should be more meat and fewer words in the papers selected for printing. The procedure of the American Society of Civil Engineers in the selection and pruning of papers might be followed. These comments, of course, apply only to the Section of Hydrology. I have no knowledge of the others.

"Under these circumstances, I feel that I am not the proper person to canvass other members for contributions to the proposed publication fund and I, therefore, suggest that someone else be appointed."

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AMERICAN GEOPHYSICAL UNION

TWENTY-FIFTH ANNUAL MEETING

SECTION OF HYDROLOGY

PAPERS

Washington, D. C.

June 1 and 2, 1944

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PAPERS, SECTION OF HYDROLOGY

WASHINGTON MEETING, JUNE 1 AND 2, 1944

A SUGGESTED METHOD OF REPORTING RAINFALL-RECORDS

D. B. Krimgold

It is now quite generally recognized among hydrologists that the reporting of precipitation in daily amounts is of rather limited value in the study of rainfall-runoff relationship. The hydrologic network of the United States Weather Bureau is reporting hourly amounts of precipitation which is quite adequate for many purposes and constitutes a great improvement over the old method of giving daily amounts and "excessive precipitation." Rainfall-records from hydrologic studies on small watersheds and plots are often reported in the form of graphs or tabulations which are essentially the reproduction of the recorded chart, corrected for time and depth when necessary. Rates in inches per hour for each period of constant rate are usually included. The publication of records in this form is quite laborious and would be prohibitive for a large network. Furthermore, the detailed breakdown which may be necessary for special studies on small plots often makes comparisons of storms difficult. There is also a tendency to report very small amounts and time-intervals which are not justified by the instruments and procedures commonly employed.

The need to express rainfall in such a manner as to show for individual storms the total amount, the rates, and the distribution of rates within the storm has been pointed out by SCHIFF, HORNER and JENS, and others, and will not be repeated. However, no practical way has yet been suggested which could be adopted by the agencies publishing rainfall records.

The following method is presented as a possible solution. It is proposed that: (1) Three basic rates of precipitation such as 0-1, 1-3, and over three inches per hour, which are most suitable for the particular hydrologic region, be used by the reporting stations.

(2) For the purpose of reporting, an individual storm will be defined as one which having started does not cease for more than one hour.

(3) No breakdown be made for amounts of 0.05 inch or less occurring in less than five minutes within the storm.

In Table 1 is shown the storm of August 15, 1940, at Bentonville, Arkansas, reported by a detailed breakdown, by hourly amounts, and by the method proposed by the writer.

The detailed breakdown shown in Table 1 is for certain purposes far superior to either of the other two, provided care is exercised not to read into the record more than there is in it. Depth of rainfall 0.05 inch or less, and time-readings to the nearest minute, should not be taken too seriously. The best instruments now available for extensive use are not perfected enough to consistently give records of this order of precision. It would, of course, be highly desirable to have all precipitation-records published with the greatest detail consistent with the accuracy of the measurements. This, however, may not be done for some time as it is a formidable task to undertake for an extensive network.

Of the two other breakdowns, the one proposed in this paper has many advantages and involves little if any additional work. In fact, if all storms--intense and otherwise--are considered, the work involved will probably be less than is involved in reporting rainfall by hourly amounts. The record of the storm of August 15 reported by the proposed method shows that the storm began at $0^{h}\,33^{m}$ and that the first 0.25 inch fell in the first 112 minutes at rates less than 1.0 inch per hour. This was followed by 0.45 inch in the next 17 minutes at rates of one to three inches per hour or an average rate of 1.6 inches per hour. The bulk of the rainfall, 1.55 inches, fell at rates of three inches per hour or more for 30 minutes, the high rates beginning after 0.7 inch fell in 129 minutes. The high rates were followed by 0.09 inch in five minutes at rates between one and three inches per hour and the storm tapered off with 0.04 inch in 43 minutes at rates less than one inch per hour.

It is obvious that no such information can be gained from an examination of this storm reported by hourly amounts.

Those concerned with floods on large rivers may see little or no advantage in the proposed method, but the hydrologists, agriculturists, and engineers concerned with drainage-basins of a

Table 1--Precipitation August 15, 1940, at Bentonville, Arkansas, reported by various methods

Date	Time	Time-interval	Accumulated depth	Intensity each time-interval
1940	h m	m	in	in/hr
Detailed breakdown				
Aug. 15	01 33	0	0.00	0.00
	01 38	5	0.05	0.60
	01 59	21	0.07	0.06
	02 10	11	0.08	0.05
	00 19	9	0.13	0.33
	02 29	10	0.15	0.12
	02 49	20	0.16	0 03
	03 18	29	0.20	0.08
	03 25	7	0.24	0.34
	03 28	3	0.34	2.00
	03 30	2	0.36	0.60
	03 35	5	0.54	2.16
	03 36	1	0.55	0.60
	03 42	6	0.68	1.30
	03 47	5	1.00	3.84
	03 50	3	1.12	2.40
	03 53	3	1.30	3.60
	04 00	7	1.75	3.86
	04 06	6	2.05	3.00
	04 09	3	2.10	1.00
	04 12	3	2.25	3.00
	04 17	5	2.34	1.08
	04 30	13	2.35	0 05
	04 59	29	2.36	0.02
	05 00	1	2.38	1.20

Hourly amounts

01^h	02^h	03^h	04^h	05^h	06^h	07^h	08^h	09^h	10^h	11^h	12^h
..	0.07	0.11	1.57	0.63	..	..	..	..	..	..	..

Proposed method

$$\text{Distribution} = \frac{\text{inch} + \text{inch} + \dots}{\text{min.} + \text{min.} + \dots} = \text{Total in } \frac{\text{inch}}{\text{hr min}}$$

For Aug. 15 beginning at $01^h\ 33^m$:

$$\frac{0.25 + 0.45 + 1.55 + 0.09 + 0.04}{112 + 17 + 30 + 5 + 43} = \frac{2.38 \text{ in}}{3 \text{ hr } 27 \text{ min}}$$

couple of hundred acres, or with fields of 80, 40, 20, 10, and fewer acres, or even small plots, should find the proposed method of value. There is already a good deal of information available on infiltration-rates of various soils and vegetal cover. With such information, and precipitation-data reported as suggested above, the hydrologist engaged in flood-forecasting on minor tributaries may obtain a fair idea of expected runoff in the area with which he is concerned. The agriculturist can estimate fairly closely how much of the rainfall entered the soil. The investigator of effects of land-use can compare more intelligently erosion and runoff from small watersheds and plots in different locations. By studying rainfall-records presented in such a way, and other pertinent data, the agronomist may be in a far better position to judge whether a plant or crop is suited to a given locality.

The writer realizes that the determination of the classes for each reporting precipitation-station will involve considerable study and will, with our present knowledge of infiltration, not be the last word. It is felt, however, that the scheme has merit and should be given consideration by those engaged in reporting rainfall-data and in analysis of rainfall, runoff, and erosion on small watersheds, individual fields, and plots. To test the practicability of the suggested scheme, the writer examined a number of storms recorded in connection with the runoff-studies of the Soil Conservation Service near Colorado Springs, Colorado, Bentonville, Arkansas, and Edwardsville, Illinois. Table 2 shows how storms in widely different hydrologic regions can be reported.

The values given in Table 2 are based on basic rates of 0-1, 1-3, and three inches per hour or more. In actual practice these basic rates need not necessarily be the same for stations representing such diverse conditions. The arrangement of entries under "Distribution" and "Totals" in Table 2 was used to conform to the format of the Transactions; it is the author's intention in publishing rainfall-records that these entries be arranged as storm under "proposed method" in Table 1.

If the proposed scheme is adopted, it may be well to consider the compilation of past records from recording stations. The work involved, if properly organized, would prove a worthwhile post-war project in which the services of a considerable number of "white collar" workers can be utilized.

Soil Conservation Service,
Washington 25, D. C.

Table 2--Selected storms near Colorado Springs, Colorado, Bentonville, Arkansas, and Edwardsville, Illinois, reported by the proposed method

Date	Time began	Distribution		Totals	
		Rainfall	Time-intervals	Rainfall	Time
	h m	in	min	in	hr min
Colorado Springs, Colorado					
Apr. 18, 1942	08 12	1.11	858	1.11	14 18
June 10, 1941	13 00	0.30 + 0.22 + 0.38	30 + 8 + 142	0.90	3 00
July 1, 1940	13 20	0.04 + 0.54 + 0.04	2 + 8 + 6	0.62	0 16
July 25, 1941	14 48	0.05 + 0.24 + 0.09	6 + 8 + 34	0.38	0 48
Sep. 30, 1940	13 46	0.37 + 0.04	10 + 20	0.41	0 30
Bentonville, Arkansas					
June 1, 1941	06 49	0.05 + 0.15 + 0.55 + 0.15 + 0.14	7 + 6 + 8 + 4 + 36	1.04	1 01
June 28, 1940	10 10	0.34 + 0.66 + 0.45 + 0.28	39 + 11 + 18 + 152	1.73	3 40
July 19, 1940	11 01	0.03 + 0.00 + 0.78 + 0.20 + 0.22 + 0.01	5 + 29 + 24 + 37 + 8 + 16	1.24	1 59
Aug. 17, 1940	01 23	0.16 + 0.01 + 0.46 + 0.09 + 0.15 + 0.90	7 + 10 + 26 + 75 + 6 + 270	1.77	6 34
Aug. 17, 1941	17 09	0.38 + 0.53 + 0.12	23 + 13 + 115	1.03	2 31
Sep. 3, 1940	05 10	0.08 + 0.50 + 0.23 + 0.42 + 0.42 + 1.07	5 + 11 + 56 + 5 + 11 + 502	2.72	9 50
Sep. 17, 1941	16 56	0.04 + 0.30 + 0.05 + 0.15 + 0.14	5 + 9 + 6 + 6 + 48	0.68	1 14
Nov. 9, 1940	03 10	0.49	540	0.49	9 00
Nov. 25-26, 1940	16 28	1.03	500	1.03	8 20
Dec. 31, 1940-Jan. 1, 1941	18 30	0.56 + 0.18 + 1.75	223 + 5 + 542	2.49	12 50
Edwardsville, Illinois					
Apr. 19, 1941	12 43	1.00	465	1.00	7 45
May 17, 1943	15 05	0.14 + 0.49 + 0.25 + 0.31 + 0.41 + 1.04	61 + 7 + 12 + 407 + 16 + 452	2.64	15 55
July 17, 1938	04 42	0.94 + 0.41 + 0.22 + 2.49 + 0.28	482 + 17 + 27 + 113 + 224	4.34	14 23
July 27, 1938	15 57	0.22 + 0.03	6 + 56	0.25	1 02
July 31, 1938	17 44	0.15 + 0.56	5 + 113	0.71	1 58
Aug. 5, 1938	22 48	0.16 + 0.26	4 + 38	0.42	0 42
Sep. 2, 1941	07 31	0.05 + 0.15 + 0.06 + 0.38 + 0.02 + 0.54 + 0.10	3 + 3 + 11 + 12 + 16 + 9 + 9	1.30	1 03
Nov. 7, 1938	03 32	1.33	464	1.33	7 44
Feb. 9, 1939	09 30	0.65 + 0.24 + 0.06	705 + 5 + 240	0.95	15 50

DISCUSSION

A. K. SHOWALTER (U. S. Weather Bureau, Washington 25, D. C.)--This paper suggests a method of publication of definite merit for users of hydrologic data concerned with the time-distribution of rainfall in the immediate vicinity of the rainfall-station. However, if the hydrologist or agriculturist becomes interested in any interpolation of average depths of rainfall over even the very smallest areas then records for three or more stations must be considered. Such studies immediately reveal the urgent need for electrical synchronization of autographic records of rainfall in dense networks. The method Mr. KRIMGOLD proposes would be a desirable added feature but could not supplant the present form of publication for the bulk of users. Postwar may bring many improvements and additions in instrumentation and publication; however, judicious use of Government funds will require that careful surveys be made of the demands for publishing data. A small number of irregular users can refer to data in manuscript, a slightly larger number can be served with photocopies, but as users of data increase in number and regularity the need for special processing and publication of data increases.

HYDROLOGY OF SMALL WATERSHEDS UNDER WINTER CONDITIONS OF SNOW-COVER AND FROZEN SOIL

Walter U. Garstka

This is a progress-report dealing for the most part with the hydrology of farm lands under winter conditions of snow-cover and of frozen soil. The observations upon which this progress-report is based were made on two cultivated watersheds and one wooded watershed near East Lansing, Michigan, by the Soil Conservation Service in cooperation with the Michigan Agricultural Experiment Station.

Records of precipitation and runoff began January 21, 1941, at Cultivated Watershed "A", February 13, 1941, at the Wooded Watershed, and March 26, 1941, at Cultivated Watershed "B". Precipitation-gages (elevation 840 feet) at the Wooded Watershed are at latitude 42°48'52", longitude 84°23'00" (in SW1/4 of SW1/4, Section 13, Twp. 5N, Range 1 W of the Michigan meridian). Precipitation-gages (elevation 888 feet) at the cultivated watersheds are at latitude 42°48'08", longitude 84°29'29" (in NE 1/4 of SW 1/4 of Section 30, Twp. 4N, Range 1 W of the Michigan meridian).

Figure 1, a map of the cultivated watersheds, shows the location of hydrologic instruments. Figure 2 is a general view, looking west, of the hydrologic instrumentation at the cultivated watersheds. The non-recording rain-and-snow gage is an eight-inch United States Weather Bureau type. The shielded gage is a similar instrument protected by a NIPHER shield of sheet-metal construction with wire-screen splash-guard patterned after the design developed at the North Appalachian Experimental Watershed of the Soil Conservation Service near Coshocton, Ohio.

The recording rain-and-snow gage (of FERGUSSON design) has nine-inch capacity, and is operated with a chart-holding clock making one revolution in 12 hours.

The hygrothermograph is an instrument with hair-actuated humidity-recording element and liquid-filled temperature-element. It is operated with a clock making one revolution per week. Figure 3 shows the precipitation-gages at the cultivated watersheds.

The runoff- and erosion-measuring installations consist of an approach section leading to a type 3-H sheet-metal flume, as designed by the Soil Conservation Service and the National Bureau of Standards, having a capacity of 30 cubic feet per second of flow. The runoff-recorder is of reversing-pen design with a ratio of five inches of chart equal to a 12-inch depth of water in the flume. The recorder-clock is usually operated at the rate of one revolution in 12 hours.

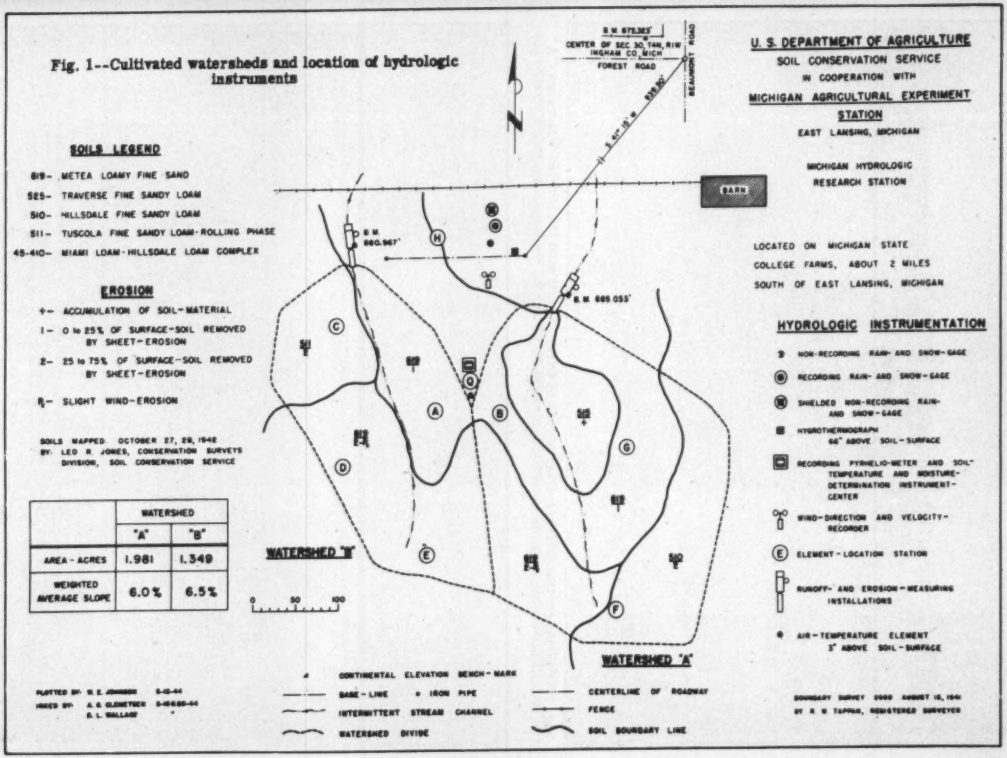
The erosion-measuring installations consist of "silt"-boxes having a storage-capacity of 320 cubic feet, and equipped with eight-foot wier-plates, RAMSER divisors, and overflow catchment-tanks. Figure 4 shows these structures at Cultivated Watershed "A" after a blizzard.

The wind direction-and-velocity recording installation, placed in complete operation April 17, 1944, consists of a 25-foot tower with three-cup anemometer (1/60-mile contact) and vane, as developed by the Soil Conservation Service. The recorder, which registers velocity and direction in octants for one minute out of each quarter-hour on a weekly chart, is operated together with a totalizer which counts every sixtieth mile of wind-movement.

The pyrheliometric installation consists of a ten-junction thermoelectric pyrheliometer (located on the roof of the main instrument-shelter) and an automatic recording-potentiometer having a full-scale deflection of four millivolts. The recorder is usually operated at a chart-speed of two inches per hour, and at times at three inches per hour. Monthly totals of solar and sky radiation for 1943, presented in Table 1, may be of interest.

The main instrument-shelter houses a switch-panel for a manually operated network of 33 copper-constantan thermocouples for measuring soil-temperature at various places in the watersheds. There is also a switch-panel for a network of 44 gypsum (calcium sulphate) soil-moisture blocks as developed by BOUYOUCOS and MICK. The wind velocity-and-direction recorder and the totalizer are found in this instrument-shelter. Continuous records during the winter season of soil-temperatures at selected depths at various places in the watersheds are produced by a 16-circuit, three-wire automatic resistance-thermometer recorder. A portion of the center's instrument-panel appears in Figure 5.

Fig. 1--Cultivated watersheds and location of hydrologic instruments


B.M. 675.383'
CENTER OF SEC. 30, T4N, R1W
INGHAM CO. MICH.
FOREST ROAD
BEAUMONT ROAD
N 67° 01' E 1328.50'
N
BARN
B.M. 660.947'
B.M. 669.033'
SOILS LEGEND
BIB- METEA LOAMY FINE SAND
SES- TRAVERSE FINE SANDY LOAM
SIO- HILLSDALE FINE SANDY LOAM
SII- TUSCOLA FINE SANDY LOAM-ROLLING PHASE
45-410- MIAMI LOAM-HILLSDALE LOAM COMPLEX
EROSION
+- ACCUMULATION OF SOIL-MATERIAL
1- 0 to 25% OF SURFACE-SOIL REMOVED BY SHEET-EROSION
2- 25 to 75% OF SURFACE-SOIL REMOVED BY SHEET-EROSION
R- SLIGHT WIND-EROSION
SOILS MAPPED OCTOBER 27, 28, 1942
BY: LEO R. JONES, CONSERVATION SURVEYS DIVISION, SOIL CONSERVATION SERVICE
WATERSHED "B"
WATERSHED "A"
0 50 100
CONTINENTAL ELEVATION BENCH-MARK
BASE-LINE
IRON PIPE
INTERMITTENT STREAM CHANNEL
WATERSHED DIVIDE
CENTERLINE OF ROADWAY
FENCE
SOIL BOUNDARY LINE
U. S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE
IN COOPERATION WITH
MICHIGAN AGRICULTURAL EXPERIMENT STATION
EAST LANSING, MICHIGAN
MICHIGAN HYDROLOGIC RESEARCH STATION
LOCATED ON MICHIGAN STATE COLLEGE FARMS, ABOUT 2 MILES SOUTH OF EAST LANSING, MICHIGAN
HYDROLOGIC INSTRUMENTATION
NON-RECORDING RAIN- AND SNOW-GAGE
RECORDING RAIN- AND SNOW-GAGE
SHIELDED NON-RECORDING RAIN- AND SNOW-GAGE
HYGROTHERMOGRAPH 66" ABOVE SOIL-SURFACE
RECORDING PYRHELIO-METER AND SOIL-TEMPERATURE AND MOISTURE-DETERMINATION INSTRUMENT-CENTER
WIND-DIRECTION AND VELOCITY-RECORDER
ELEMENT-LOCATION STATION
RUNOFF- AND EROSION-MEASURING INSTALLATIONS
AIR-TEMPERATURE ELEMENT 3" ABOVE SOIL-SURFACE
BOUNDARY SURVEY 2000 AUGUST 10, 1944
BY R. B. TAPPAN, REGISTERED SURVEYED
PLOTTED BY: H. E. JOHNSON 5-12-44
INKED BY: A. G. GLOMSTEEN 5-26-&30-44
D. L. WALLACE "

	WATERSHED	
	"A"	"B"
AREA - ACRES	1.981	1.349
WEIGHTED AVERAGE SLOPE	6.0%	6.5%

Fig. 2--Hydrologic installations, from hayloft of barn, looking west [Cultivated Watershed "A" runoff-and-erosion station on left (Photograph by Walter L. Wickman, January 7, 1943)]

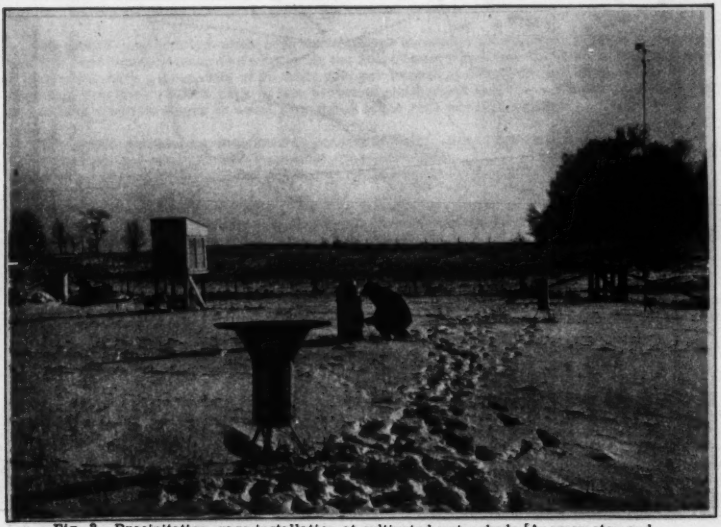


Fig. 3--Precipitation-gage installation at cultivated watersheds [Anemometer and wind-vane tower on right, temperature-and-humidity recorder-shelter on left (Photograph by Walter L. Wickman, January 4, 1943)]

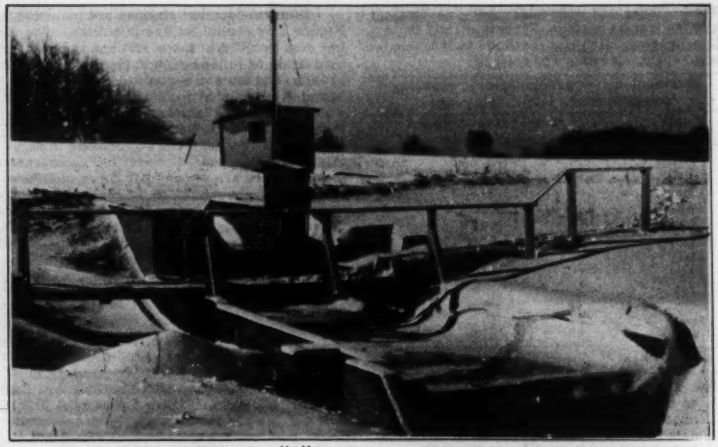


Fig. 4--Cultivated Watershed "A" February 2, 1942 (Photograph by W. U. Garstka)

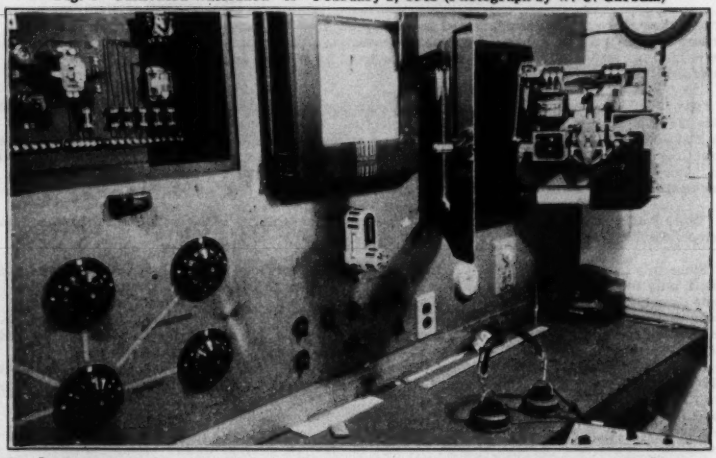


Fig. 5--Recorder and switch-panel at main instrument-shelter at cultivated watersheds [Large switches in lower left-hand corner in copper-constantan thermocouple circuit; potentiometer used in it located beyond lower left-hand margin and not visible; wind-recorder and synchronizer-relays are above thermocouple-switches; recorder with closed door in upper center is automatic potentiometer used with pyrheliometer and immediately below is thermostat-switch, controlling center's electric heating-system; small switches just below it are part of soil-moisture block-system (thermocouple and block-switch connections installed by Robert A. Sanderson); earphones on table used with specially built alternating-current conductivity-bridge in lower right-hand corner for determining block-resistances; clock-like instrument below open door of recorder is wind-mileage totalizer; wind-direction and velocity recorder mounted on separate bench to right, not visible; swung-out mechanism is that of resistance-thermometer soil-temperature recorder (Photograph by W. U. Garstka, May 13, 1944)]

Table 1--Total sky and solar radiation incident upon horizontal surface, Pyrheliometric Station, East Lansing, Michigan (Latitude 42°42', longitude 84°28', elevation 899 feet)

Thermoelectric pyrheliometer; recording potentiometer, 4-millivolt range	
Month 1943	Total gram-calories per square centimeter
Jan.	4,229
Feb.	6,566
Mar.	10,046
Apr.	12,909[a]
May	10,776[a]
June	15,730
July	15,443
Aug.	12,147
Sep.	9,794
Oct.	6,074
Nov.	3,137
Dec.	2,964
Total	109,815[a]

[a] Breakage of pyrheliometer in hailstorm resulted in loss of record for period April 27, 1943, to May 7, 1943; values used in lieu of missing data based on an average of 20 days, ten before and ten after, break in record.

Element-location stations are indicated in Figure 1 by capital letters in circles. The number and position of these stations is based upon evaluation of volume-weight (apparent specific gravity) and moisture-equivalent of 216 soil-samples selected at random at 18 spots in the watershed-area. Samples were taken by six-inch depths down to six feet. This study indicated about five per cent significance in sampling the watersheds, in so far as the characteristics studied are concerned. Since moisture-equivalent and volume-weight reflect generally water-retaining characteristics of a soil which in turn are important in conditioning the soil's thermodynamic characteristics, it is reasonable to assume that the five per cent significance-figure applies likewise to the data produced by the temperature and moisture-measuring network.

The project's Wooded Watershed is located on lands of the Rose Lake Wildlife Experiment Station of the Michigan State Department of Conservation about ten miles northeast of East Lansing, Michigan. Figure 6 shows the precipitation-gages and the hygrothermograph-shelter. These instruments are identical with those at the cultivated watersheds. Air-temperature three inches above the soil-surface and soil-temperatures one inch and six inches below the soil-surface are recorded by a three-pen vapor-pressure type thermograph operated with a clock making one revolution per week. Figure 7 is a map for location of soils and instruments of the Wooded Watershed.

The runoff- and erosion-measuring installation and the recording instrument are identical with those at the cultivated watersheds with one exception. The "silt"-box capacity is 200 cubic feet. The installation is shown in Figure 8. The forest at the Wooded Watershed is a middle-aged second-growth oak-hickory stand, well stocked. The average height of dominant trees is between 70 and 80 feet. The Forestry Department of the Michigan Agricultural Experiment Station has made a complete ecological survey of the Wooded Watershed.

Table 2 affords a comparison of the distribution of percentages of the watershed drainage-areas in slope-classes.

Since this progress-report deals principally with the hydrology of farm lands under winter conditions, only the winter summaries are presented here although hydrologic observations are continued throughout the year. Table 3 lists precipitation and runoff at the three watersheds for the winter season 1941-42. Table 4 gives similar information for the winter season 1942-43. As soil-temperature recording equipment was in operation during this winter, the period November 29, 1942, to April 20, 1943, is considered as being the winter season since the soil first froze on November 26 and the frost finally disappeared from the soil on April 20. Table 5 covers the period November 9, 1943, to April 18, 1944, during the past winter. During the winter of 1941-42 the soil-surface was bare, the cultivated watersheds having produced a crop of corn in 1941. Rye was seeded late in September, but practically all of the seed was washed out in a number of storms which occurred early in October. The failure of establishment of the rye cover-crop resulted in the bare soil-surface. It is to be noted that from 72 to 80 per cent of the precipitation for the winter season of 1941-42 ran off at the cultivated watersheds, whereas only nine per cent ran off in the woods. The winter of 1941-42 was what is known as an "open" one, with but little snow.

During the winter season of 1942-43 the soil-surface was protected with a stubble-and-litter layer amounting to 1,650 pounds per acre (air-dry weight) at Cultivated Watershed "A", and 1,450 pounds per acre at Cultivated Watershed "B". This was a winter of more or less persistent snow-cover. Frost penetration was not very great during most of the winter. Of the winter precipitation there ran off at the cultivated watersheds 16.6 to 20.5 per cent, but only 2.6 per cent ran off from the wooded watershed.

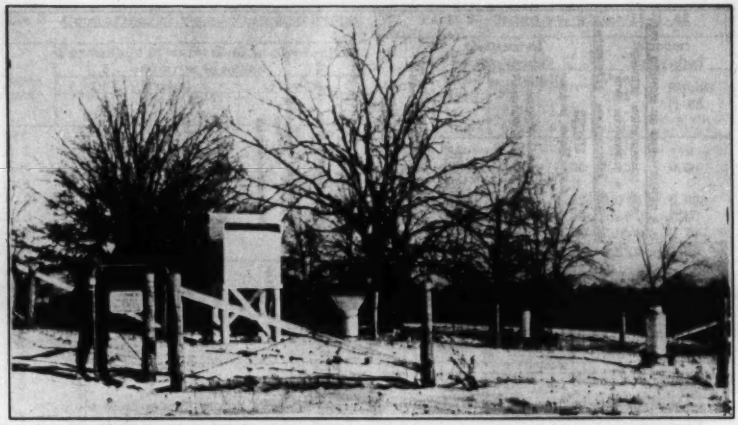


Fig. 6--Precipitation-gages and temperature-and-humidity recording instrument-shelter at Wooded Watershed (Photograph by Dr. Durward Allen, Michigan State Department of Conservation, January 1942)

Fig. 8--Runoff-and-erosion measuring installation at Wooded Watershed on lands of Rose Lake Wildlife Experiment Station of Michigan State Department of Conservation [Oscar Warback is holding 2-unit section of metal Mount Rose type snow-sampling tube (Photograph by W. U. Garstka, February 2, 1942)]

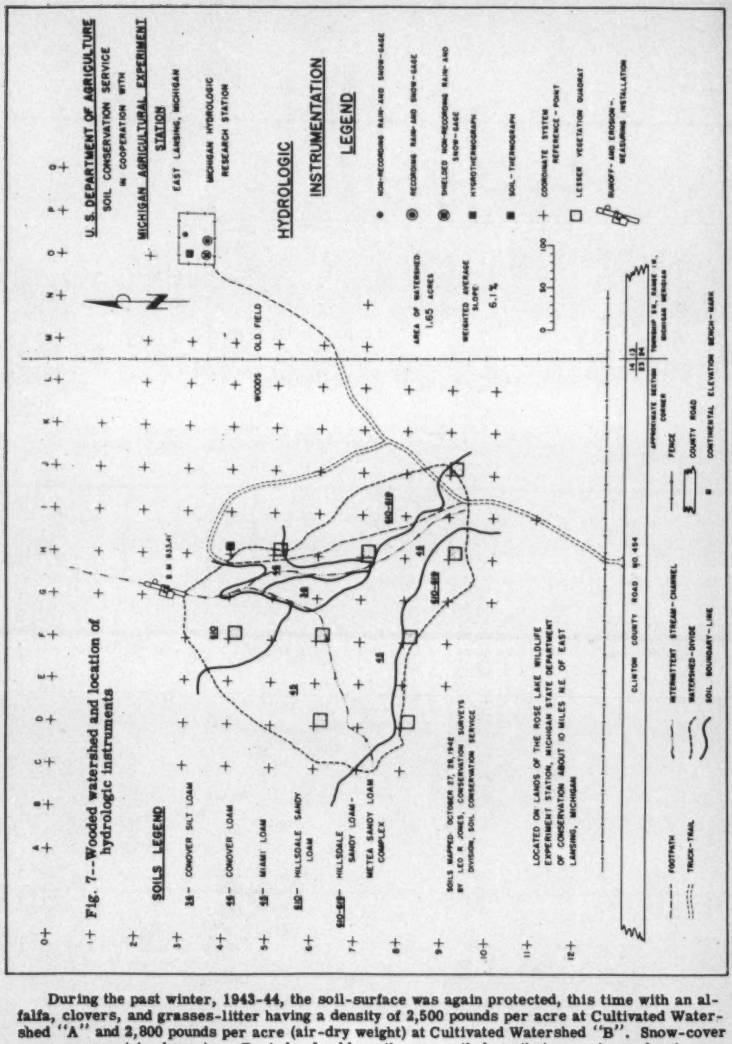


Fig. 7--Wooded watershed and location of hydrologic instruments

During the past winter, 1943-44, the soil-surface was again protected, this time with an alfalfa, clovers, and grasses-litter having a density of 2,500 pounds per acre at Cultivated Watershed "A" and 2,800 pounds per acre (air-dry weight) at Cultivated Watershed "B". Snow-cover was evanescent in character. Periods of cold weather prevailed, so that a maximum frost-pene-

Table 2--Comparison of slope-class distribution

Slope-class	Percentage of watershed in slope-class and area in acres		
	Cultivated		Wooded
	"A" 1.98	"B" 1.35	1.65
	pct	pct	pct
2-3	23	3	17
3-4	14	17	3
4-6	21	29	30
6-8	12	29	34
8-10	21	10	6
10-12	9	12	5
12-14	0	0	5
Weighted average slope	6.0	6.5	6.1

Table 3--Summary, winter 1941-42

Month	Cultivated watersheds[a]			Wooded watershed	
	Precipitation	Runoff "A" (1.98, 6.0[b])	Runoff "B" (1.35, 6.5[b])	Precipitation	Runoff (1.65, 6.1[b])
1941	in	in	in	in	in
Dec.	1.59	0.00	0.00	1.43	0.00
1942					
Jan.	1.73	0.37	0.32	2.07	0.00
Feb.	0.56	0.28	0.24	0.64	0.00
Mar.	3.26	4.49	5.90	4.95	0.79
Totals	7.14	5.14	6.46	9.09	0.79
Per cent	100	72	90	100	9

[a] Bare-soil surface at cultivated watersheds.
[b] Area in acres and average slope in per cent.

Table 4--Summary, winter 1942-43

Period or Month	Cultivated watersheds[a]			Wooded watershed	
	Precipitation[b]	Runoff "A" (1.98, 6.0[c])	Runoff "B" (1.35, 6.5[c])	Precipitation[b]	Runoff (1.65, 6.1[c])
1942	in	in	in	in	in
Nov. 26-30	0.41	0.000	0.000	0.43	0.000
Dec.	2.47	0.054	0.011	3.02	0.000
1943					
Jan.	1.61	0.000	0.000	2.20	0.000
Feb.	1.05	0.602	0.680	1.47	0.034
Mar.	2.58	0.861	1.183	2.68	0.250
Apr. 1-20	1.02	0.000	0.000	1.31	0.000
Totals	9.14	1.517	1.874	11.11	0.284
Pct precipitation which ran off	100.0	16.6	20.5	100.0	2.6

[a] Soil-surface protected with a layer of oats-stubble, clover, and alfalfa litter having a density of 1650 pounds per acre in "A", and 1450 pounds per acre (air-dry weight) in "B". [b] Water-equivalent, as measured in a standard rain-gage. [c] Area in acres and average slope in per cent.

Table 5--Summary, winter 1943-44

Period or Month	Cultivated watersheds[a]			Wooded watershed	
	Precipitation[b]	Runoff "A" (1.98, 6.0[b])	Runoff "B" (1.35, 6.5[b])	Precipitation[b]	Runoff (1.65, 6.1[c])
1943	in	in	in	in	in
Nov. 9-30	0.32	T	T	0.29	0.000
Dec.	0.37	0.000	0.000	0.41	0.000
1944					
Jan.	1.30	0.069	0.116	1.22	0.000
Feb.	1.74	1.959	1.947	1.94	0.000
Mar.	2.48	1.680	1.725	2.65	0.018
Apr. 1-18	1.97	0.040	0.048	1.19	0.000
Totals	8.18	3.748	3.836	7.70	0.018
Pct precipitation which ran off	100.0	45.8	46.9	100.0	0.2

[a] Soil-surface protected with a layer of alfalfa, clovers, and grasses litter having a density of 2500 pounds per acre in cultivated "A", and 2800 pounds per acre (air-dry weight) in "B". [b] Water-equivalent as measured in a standard rain-gage. [c] Area in acres and average slope in per cent.

Note for Tables 4 and 5: Soils at the cultivated watersheds are Metea, Hillsdale, and Miami, and at the wooded watershed they are Miami and Hillsdale.

tration of 30 inches took place at the cultivated watersheds, the presence of the mulch-layer notwithstanding.

Precipitation, for the winter season from November 9, 1943, to April 18, 1944, as measured in the standard gage, was 8.18 inches at the cultivated watersheds and 7.70 inches at the Wooded Watershed. Runoff at Cultivated Watershed "A" was 45.8 per cent and at Cultivated Watershed "B" 46.9 per cent.

Table 6--Snow-surveys, winter 1942-43, cultivated watersheds
(Snow-surveys performed by W. U. Garstka, Walter L. Wickman, and Allison W. Blanshine)

Date	Cultivated watershed "A"				Cultivated watershed "B"			
	Time	Mean snow-depth	Water-equiva-lent	Den-sity	Time	Mean snow-depth	Water-equiva-lent	Den-sity
1942	h m	in	in	pct		in	in	pct
Dec. 21	16 00 EWT	6.5	0.86	13.2	a	a	a	a
1943								
Jan. 4	09 30 EWT	6.5	0.71	11.0	10 00 EWT	7.1	0.78	11.0
Jan. 11	14 00 EWT	5.9	0.86	14.6	14 30 EWT	6.7	0.98	14.6
Jan. 16	14 00 EWT	10.2	1.40	13.7	15 00 EWT	11.0	1.75	15.9
Jan. 23	14 30 EWT	12.5	b	b	15 00 EWT	11.9	b	b
Feb. 6	10 00 EWT	8.8	b	b	10 30 EWT	9.0	b	b
Feb. 8	15 00 EWT	8.2	2.57	31.3	15 25 EWT	8.4	2.45	29.0
Feb. 19	08 30 CWT	6.1	2.30	37.7	09 00 CWT	6.4	2.43	37.7
Feb. 22	11 00 CWT	6.0[cd]	2.80[cd]	46.3[cd]	11 30 CWT	5.7[ce]	2.30[ce]	40.3[ce]
Mar. 5	11 00 CWT	None	...	...	.....	None	...	...
Mar. 8	11 00 CWT	4.0	...	...	11 00 CWT	3.9	...	...

[a] Combined measurements for "A" and "B". [b] Air-temperatures prevented use of snow-tube. [c] Figures for snow-drift. [d] Water-equivalent for watershed 0.111. [e] Water-equivalent for watershed 0.163.

Table 7--Snow-surveys, winter 1942-43, wooded watersheds
(Snow-surveys performed by W. U. Garstka, Walter L. Wickman, and Allison W. Blanshine)

Date	Time	Average snow-depth	Water-equivalent	Density
1942	h m	in	in	pct
Dec. 22	14 30 EWT	7.5	1.06	14.1
1943				
Jan. 4	14 00 EWT	7.6	0.96	12.6
Jan. 11	10 30 EWT	6.9	1.09	15.8
Jan. 16	16 30 EWT	10.9	1.76	16.1
Jan. 23	09 30 EWT	15.5	a	a
Jan. 25	09 30 EWT	11.3	a	a
Feb. 8	11 10 EWT	9.2	2.42	26.2
Feb. 19	10 30 CWT	8.3	2.33	28.0
Feb. 20	15 35 CWT	3.4	1.20	35.6
Feb. 22	15 40 CWT	2.4	0.76[b]	35.4[b]
Feb. 24	13 30 CWT	2.3[cd]	0.90[cd]	39.1[cd]
Mar. 5		Trace	...	...
Mar. 8	09 00 CWT	3.8	...	...
Mar. 11	15 30 CWT	Trace[e]	...	...

[a] Air-temperature prevented use of snow-tube. [b] One-tenth of watershed bare. [c] Figure for snow-drift. [d] Water-equivalent for watershed 0.11. [e] Trace of snow 1/4 inch to two inches deep.

Hydrologic records of the three winter seasons indicate that presence or absence of a snow-layer and the character of persistence of sub-freezing air-temperatures may have an influence at least as important as the presence or absence of a mulch-layer (on agricultural land) in conditioning the winter runoff-producing potentialities of farm lands.

Only 0.2 per cent of the 1943-44 winter precipitation ran off in the woods. The normal precipitation as established by a 40-year United States Weather Bureau record at East Lansing, Michigan, is 30.52 inches.

Practically no erosion was caused by the winter-season runoffs during the three winters. When the soil-surface was bare, in the spring of 1942, the thaw took place in a period of almost three weeks of precipitation-free weather. Had any rain fallen during that time, serious erosion would

have occurred. The mulch-layer effectively prevented erosion during the winter seasons of 1942-43 and 1943-44.

The winter of 1942-43 produced some of the greatest snowfalls recorded in some parts of Michigan. The deepest accumulation of snow at the East Lansing stations was 16.5 inches on January 21, 1943. Snow-depth and water-equivalent varied greatly throughout the winter, as is to be expected. Table 6 presents in detail the snow-survey data obtained at the cultivated watersheds during the winter season of 1942-43. It is difficult to perform snow-surveys in this region because, in many cases, snow-depths are so shallow as to restrict efficient use of the Mount Rose snow-tube.

The figures given are based upon at least 20 tube-samples taken at random in each watershed, and their water-equivalent determined by weight. It is often difficult to get satisfactory data because of suddenly changing and relatively extreme differences in air-temperatures which are encountered in the course of the day's work. The lower lying layers of snow may be considerably colder or warmer than the air, causing sticking in the snow-tubes, or else preventing the core from remaining within the tube and thus making it impossible to lift the snow-samples. Snow in a "ripe" condition had a density of from 40 to 46 per cent, which means that its water-equivalent was from about 2-1/2 to 2 inches of snow per inch of water. Freshly fallen snow has been observed to have equivalents of from ten inches of snow to equal an inch of water up to as high as 15 inches of snow to equal an inch of water. Snow-survey data for the Wooded Watershed is presented in Table 7.

The accurate measurement of both the summer and especially of the winter precipitation is of fundamental hydrologic importance. At both the cultivated and wooded watersheds, the precipitation-measuring equipment consists of a recording gage with a ratio of 1-1/2 inches of chart equaling one inch of water, the standard United States Weather Bureau type non-recording eight-inch gage, and a NIPHER shielded non-recording eight-inch gage. The records from these gages show great differences. Rainfall-differences are not very great, but fine mists or snows produced at times differences of several hundred per cent, in comparing the catch in the recording gage and that in the shielded gage.

An effort is made at the end of each snowstorm to ascertain the validity of precipitation-gage data by the performance of a snow-survey. There have been only a few opportunities to do this because many of the snowstorms in southern Michigan are accompanied by relatively high winds which continue to blow for some time after the snowfall has ceased. This results in drifting which makes it impossible to secure any adequate concept of the accuracy of measurement of the snowfall by the various gages. Snowfall-totals over larger areas are affected, it is believed, to a negligible extent by snow-drifting. However, very critical differences in the water-content on small areas may be introduced by wind following snowfall. It has been found necessary to postpone until the wind has died down the making of a snow-survey, not only at the cultivated watersheds but also at the Wooded Watershed, because of the relatively free access of wind in the defoliated oak-hickory woods. Fortunately, there were a number of snowstorms in the winter season of 1942-43 which did offer an opportunity to compare the relative accuracy of the different gages. These data are presented in Tables 8 and 9. A perusal of these Tables indicates clearly a remarkable consistency of agreement of snow-survey data with that of the shielded gage, whereas the standard-gage and the recording-gage totals are erroneous, at times alarmingly so.

The data from these few storms indicates once again that thought should be given to the installation of shielded gages if an accurate measure of winter precipitation is desired. The concept of the use of shields on rain-and-snow gages is based on sound aerodynamic principles. It is interesting to note that the NIPHER shield as used at East Lansing is practically as originally designed in 1878 by P. E. NIPHER, who resided in St. Louis, Missouri, at that time.

Although a shielded gage appears to be capable of measuring with considerable accuracy the amount of winter precipitation storm by storm, it is to be recognized that only a snow-survey can yield the definite information about the water-equivalent of a snow-blanket at any selected time.

Figure 9 is a tabulation of various conditions preceding the storm of December 26-27, 1942. At the top of the sheet are charted soil-temperatures down to a depth of five feet below the surface of the soil. Air-temperatures 66 inches above the soil-surface and three inches above the soil-surface are plotted. Below these are shown snow-depths, one curve for Watershed "A", the other for Watershed "B". The element from which the three-inch air-temperature record was acquired is located on practically a flat area on the divide between the two watersheds. Snow-depths over

Table 8--Comparison of snowfall as determined by snow-surveys with amounts as measured by various rain-gages

Date	Cultivated watersheds			Wooded watershed		
	Recording gage-pail	Standard gage	Shielded gage	Recording gage-pail	Standard gage	Shielded gage
1943	in	in	in	in	in	in
	(1) Snow of January 2-4, 1943					
Jan. 2	0.08	0.11	0.15	0.13	0.12	0.18
Jan. 3	0.21	0.28	0.38	0.34	0.32	0.46
Jan. 4	0.04	0.05	0.08	0.07	0.07	0.09
Total	0.33	0.44	0.61	0.54	0.51	0.73
	Snow of January 6-9, 1943					
Jan. 6	0.04	0.05	0.08	0.06	0.09	0.11
Jan. 9	0.02	0.02	0.03	0.02	0.02	0.03
Totals						
Jan. 6-9	0.06	0.07	0.11	0.08	0.11	0.14
Jan. 2-9	0.39	0.51	0.72	0.62	0.62	0.87
	Snow-surveys					
Jan. 4	0.71("A")	0.78("B")	...	0.96	...	...
Jan. 11	0.86("A")	0.98("B")	...	1.09	...	...
Diff.						
Jan. 4-11	+0.15("A")	+0.20("B")	...	+0.13	...	...

Table 9--Comparison of snowfall as determined by snow-surveys with amounts as measured by various methods

Date	Cultivated watersheds			Wooded watershed		
	Recording gage-pail	Standard gage	Shielded gage	Recording gage-pail	Standard gage	Shielded gage
1943	in	in	in	in	in	in
Cumulative						
Jan. 2-11[a]	0.39	0.51	0.72	0.62	0.62	0.87
Jan. 14, snow	0.02	0.04	0.05	0.04	0.05	0.06
Jan. 15, snow	0.09	0.14	0.21	0.18	0.20	0.26
Jan. 16, snow	0.13	0.22	0.32	0.27	0.29	0.38
Totals						
Jan. 14-16	0.24	0.40	0.58	0.49	0.54	0.70
Jan. 2-16	0.63	0.91	1.30	1.11	1.16	1.57
	Snow-survey					
Jan. 16	1.40("A")	1.75("B")	...	1.76	...	...
Diff.						
Jan. 11[a] to 16	+0.54("A")	+0.77("B")	...	+0.67	...	...

[a] See Table 8.

the watershed varied, the depths tabulated being averages. When snow-depth remained below five to six inches there was uniformity between the temperatures in the air at 66 inches and at three inches as is shown by the almost coincidental plottings of the two air-temperature curves. It is interesting to observe that on December 13, a day of very high solar radiation, as is shown in the tabulation of hourly values in the curves below the snow-depth, the air at three inches above the surface was notably warmer than at 66 inches. Soil-temperature, under these conditions, did not respond very rapidly to air-temperature fluctuations.

This is due to the fact that as long as soil-freezing is actively progressing, soil-temperatures will not vary much from the level of 32° F, since the freezing of each gram of water releases 80 calories of heat. This heat tends to warm up the soil previously frozen and thus counteracts the depression of soil-temperatures due to low air-temperatures as long as this freezing actively proceeds. Low temperatures have been observed in the soil-surface, at times just a few degrees

above zero, but that only took place when the soil was frozen to a depth of two feet, or more, so that the zone of active freezing was so far below the surface, taking into account the speed of movement of heat-waves, that the frozen soil on the surface acted as a uniform solid. The cold from the air above it depressed surface soil-temperature in relatively short time.

It is interesting to note that with the increase in the amount of snow, a difference developed between the two air-temperature curves. Air-temperatures at three inches above ground-level were very much higher than those 66 inches above the ground. This difference persisted until the snow-depth was reduced to the five-inch to seven-inch depth. High hourly totals of solar radiation occurred on December 19 to 21--days when zero weather persisted. It has been observed that this is often the case when polar air-masses are dominant in southern Michigan. The clear and dry polar air is so transparent that very high values of solar radiation are recorded at the pyrheliometric station. It will be interesting to determine to what extent short-wave solar heat penetrates the snow and is converted to long-wave heat. Such conversion may contribute to the difference in the observed air-temperatures at the 66-inch level and at the three-inch level.

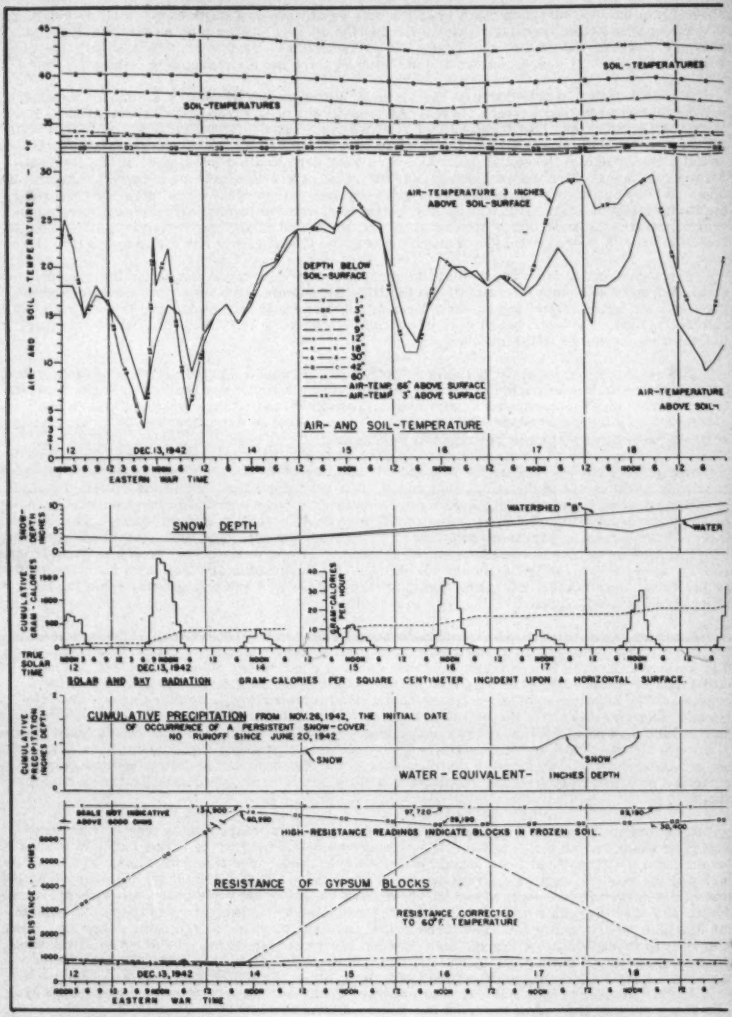
The second curve from the bottom is that of cumulative precipitation, using the standard eight-inch rain-gage data for rainfall and the NIPHER shielded non-recording eight-inch snow-gage data for snow. These totals, therefore, do not agree with those tabulated in the official daily rainfall-record. However, based upon previously discussed points, it is considered necessary to list snow as measured in the shielded gage.

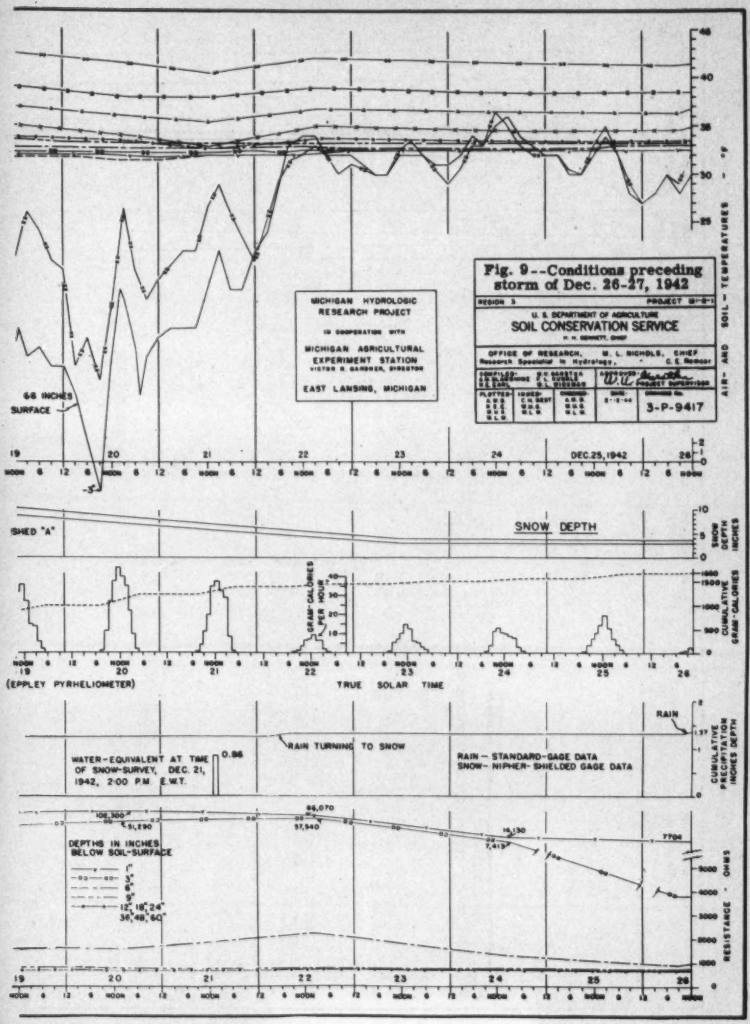
The series of curves at the bottom of Figure 9 are a graphical presentation of resistances of calcium-sulphate blocks buried at various depths below the surface of the soil. Blocks from the 12-inch to 60-inch level, showed almost identical readings, indicating unchanged soil-moisture conditions. All block-resistance data have been corrected to a temperature of 60°. The vertical scale of part of the graph has been greatly condensed.

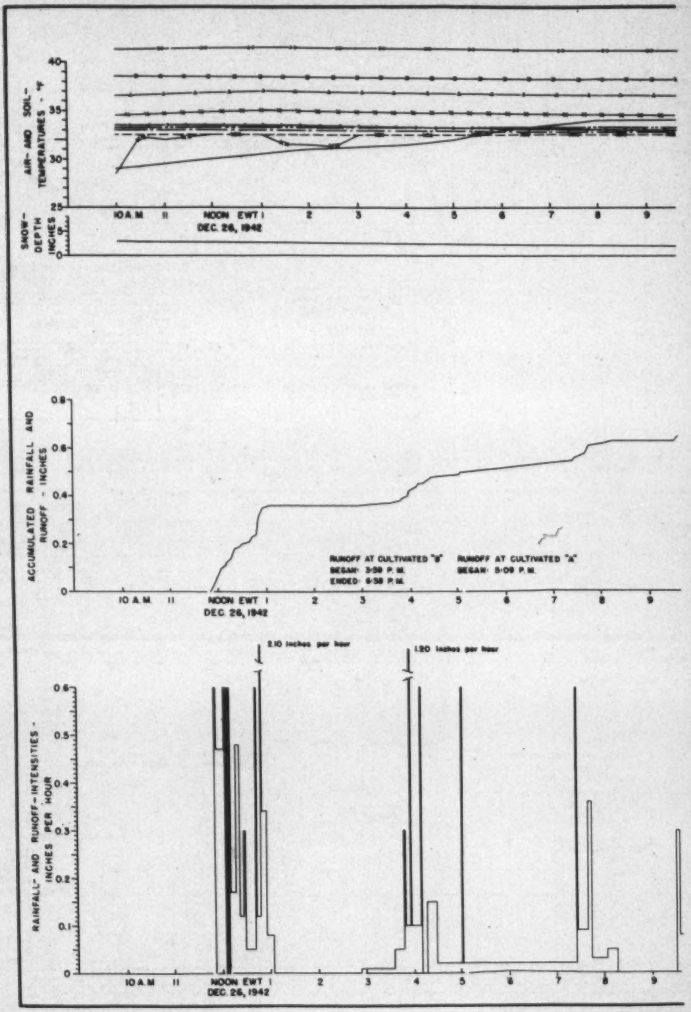
The gypsum blocks indicate the presence or absence of water. Since ice is not wet, freezing results in a drying out of the soil. This results in a very great increase in the resistance of the blocks, indicating withdrawal of liquid water. As the cold wave penetrates into the soil, as indicated by the depression of temperatures at different depths, various gypsum blocks proceed to freeze. The one-inch block remained frozen for most of the period plotted. The block at three-inch depth began to freeze sometime before December 13 and was well on its way to being frozen solidly somewhere between December 13 and 14. The block at the six-inch level likewise showed an increase in resistance, indicating that capillary tension was extracting water from the zone in which this block was located.

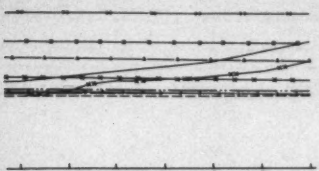
Freezing of the soil tends to translocate water from one level to another. The formation of ice in the frozen soil sets up a capillary tension which sucks water from the horizon below it. As this water reaches the frozen layer, provided there is a deficiency of heat sufficient to absorb its latent heat of fusion, this water likewise freezes and thus the capillary tension is permitted to continue. The building up of these layers of ice results ultimately in what are known as "ice-lenses". Surface-layers of the soil thus acquire volumes of water far beyond that which they are able to hold against the pull of gravity under frost-free conditions. This may result, upon thawing, in a supersaturated soil which may attain the consistency of a heavy suspension. This is one of the principal reasons why there is much trouble with construction of highways and stability of structure on alternately freezing and thawing soils which have an appreciable water-holding capacity.

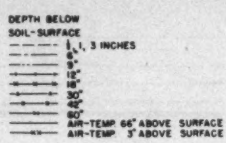
Returning to the graph of gypsum-block resistances, it is interesting to note that as snow-depth increases and as the departure in air-temperature curves for the three-inch and 66-inch levels occurs, although but little change in soil-temperatures is evident, the blocks at the three-inch and the six-inch depth stop freezing and begin to thaw. This indicates that further penetration of the cold wave has stopped and that heat from the lower horizons of the soil is expressing dominance over the cold wave. This is likewise indicated by a steady drop in the resistance of the block at the six-inch level. The block at the nine-inch level shows the same response. Part of this drop in resistance at the six-inch level is, of course, due to the movement of water from the horizon below to satisfy the deficiency which was created by the capillary attraction within the upper-lying soil-horizons. The influx of a warm air-mass on December 21 and 22 made it possible for the soil to thaw out. This is indicated by the sudden drop in resistances of the gypsum block showing that all of the frost has departed from the soil by December 25.

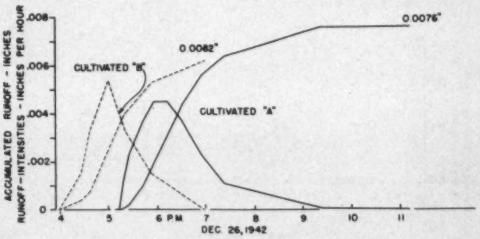

SOIL-TEMPERATURES
SOIL-TEMPERATURES
°F
AIR- AND SOIL-TEMPERATURES - °F
AIR-TEMPERATURE 3 INCHES ABOVE SOIL-SURFACE
DEPTH BELOW SOIL-SURFACE
1"
3"
6"
9"
12"
18"
30"
42"
60"
AIR-TEMP 66" ABOVE SURFACE
AIR-TEMP 3" ABOVE SURFACE
AIR-TEMPERATURE ABOVE SOIL
AIR- AND SOIL-TEMPERATURE
DEC. 13, 1942
EASTERN WAR TIME
SNOW-DEPTH - INCHES
SNOW DEPTH
WATERSHED "B"
WATER
CUMULATIVE GRAM-CALORIES
GRAM-CALORIES PER SQUARE CENTIMETER PER HOUR
TRUE SOLAR TIME
DEC. 13, 1942
SOLAR AND SKY RADIATION
GRAM-CALORIES PER SQUARE CENTIMETER INCIDENT UPON A HORIZONTAL SURFACE.
CUMULATIVE PRECIPITATION - INCHES DEPTH
CUMULATIVE PRECIPITATION FROM NOV. 26, 1942, THE INITIAL DATE OF OCCURRENCE OF A PERSISTENT SNOW-COVER
NO RUNOFF SINCE JUNE 20, 1942
SNOW
SNOW
WATER-EQUIVALENT- INCHES DEPTH
RESISTANCE - OHMS
SCALE NOT INDICATIVE ABOVE 6000 OHMS
HIGH-RESISTANCE READINGS INDICATE BLOCKS IN FROZEN SOIL.
RESISTANCE OF GYPSUM BLOCKS
RESISTANCE CORRECTED TO 60° F. TEMPERATURE
DEC. 13, 1942
EASTERN WAR TIME

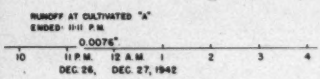

MICHIGAN HYDROLOGIC RESEARCH PROJECT
IN COOPERATION WITH
MICHIGAN AGRICULTURAL EXPERIMENT STATION
VICTOR R. GARDNER, DIRECTOR
EAST LANSING, MICHIGAN
Fig. 9--Conditions preceding storm of Dec. 26-27, 1942
REGION 3 PROJECT W-9-1
U. S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE
H. H. BENNETT, CHIEF
OFFICE OF RESEARCH, W. L. NICHOLS, CHIEF
Research Specialist in Hydrology, C. E. Ramser
3-P-9417
66 INCHES
SURFACE
AIR- AND SOIL - TEMPERATURES - °F
DEC. 25, 1942
SHED "A"
SNOW DEPTH
SNOW DEPTH - INCHES
GRAM-CALORIES PER SQ. CM. PER HOUR
CUMULATIVE GRAM-CALORIES
(EPPLEY PYRHELIOMETER)
TRUE SOLAR TIME
RAIN
WATER-EQUIVALENT AT TIME OF SNOW-SURVEY, DEC. 21, 1942, 2:00 P.M. E.W.T.
0.86
RAIN TURNING TO SNOW
RAIN — STANDARD-GAGE DATA
SNOW- HIPHER- SHIELDED GAGE DATA
CUMULATIVE PRECIPITATION - INCHES DEPTH
DEPTHS IN INCHES BELOW SOIL-SURFACE
1"
3"
6"
9"
12", 18", 24"
36", 48", 60"
RESISTANCE - OHMS


AIR- AND SOIL-TEMPERATURES - °F
40
35
30
25
10 A.M.
11
NOON EWT
1
2
3
4
5
6
7
8
9
DEC. 26, 1942
SNOW-DEPTH IN INCHES
0
ACCUMULATED RAINFALL AND RUNOFF - INCHES
0.8
0.6
0.4
0.2
0
RUNOFF AT CULTIVATED "B" BEGAN: 3:09 P.M. ENDED: 6:38 P.M.
RUNOFF AT CULTIVATED "A" BEGAN: 3:09 P.M.
RAINFALL- AND RUNOFF-INTENSITIES - INCHES PER HOUR
2.10 inches per hour
1.20 inches per hour
0.6
0.5
0.4
0.3
0.2
0.1
0

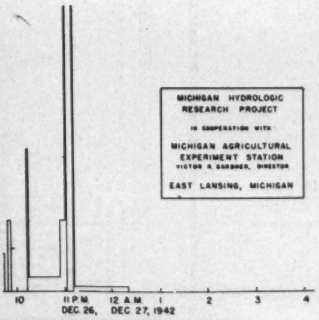








SOIL-SURFACE PROTECTED BY ALFALFA AND CLOVER LITTER AND OAT STUBBLE
CULTIVATED "A" 1600 LBS PER ACRE
CULTIVATED "B" 1400 LBS PER ACRE



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MICHIGAN AGRICULTURAL EXPERIMENT STATION
VICTOR R. GARDNER, DIRECTOR
EAST LANSING, MICHIGAN

Fig. 10--Storm of Dec. 26, 1942

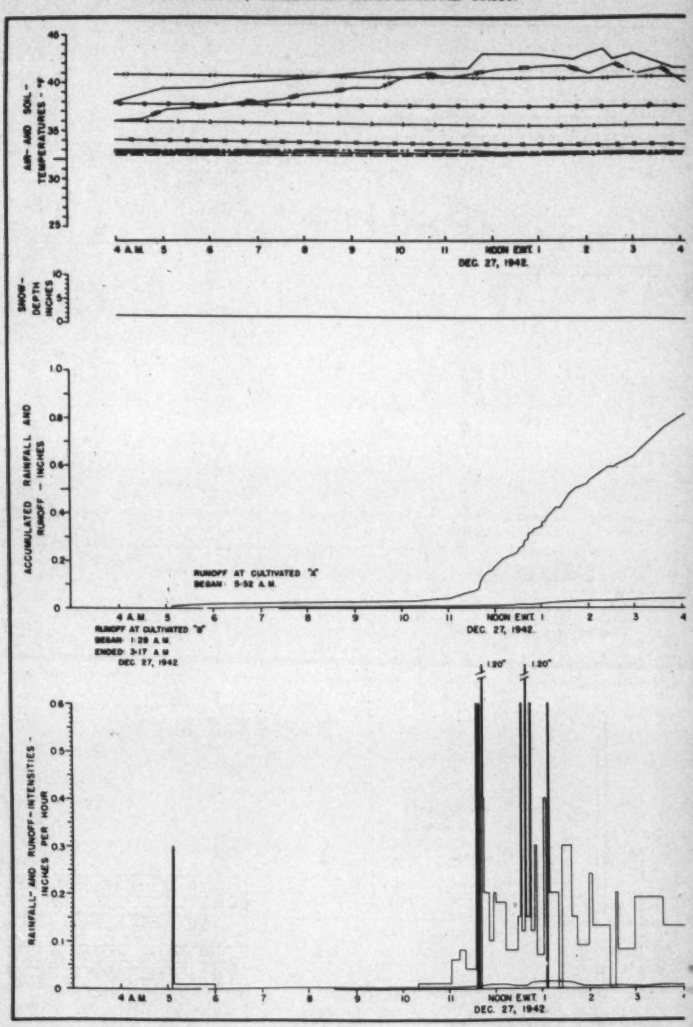
REGION 3 PROJECT MI-R-1

U. S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE
H. H. BENNETT, CHIEF

OFFICE OF RESEARCH, M. L. NICHOLS, CHIEF
Research Specialist in Hydrology, C. E. Ramser

Compiled by H. J. Gabriel, I. T. Edmonds, G. L. Hoover
Approved: W. L. Nelson, Project Supervisor

Plotted: E.S.L., C.E.R., G.L.H.
Traced: E.S.L., C.E.R., G.L.H.
Checked: A.G.S., C.E.R.
Date: 8-19-44
Drawing No. 3-P-9415


AIR- AND SOIL-TEMPERATURES - °F
45
40
35
30
25
4 A.M. 5 6 7 8 9 10 11 NOON E.W.T. 1 2 3 4
DEC. 27, 1942.
SNOW-DEPTH IN INCHES
10
5
0
ACCUMULATED RAINFALL AND RUNOFF - INCHES
1.0
0.8
0.6
0.4
0.2
0
RUNOFF AT CULTIVATED "A" BEGAN 9-52 A.M.
RUNOFF AT CULTIVATED "B" BEGAN 1-29 A.M. ENDED 3-17 A.M. DEC. 27, 1942.
4 A.M. 5 6 7 8 9 10 11 NOON E.W.T. 1 2 3 4
DEC. 27, 1942.
RAINFALL* AND RUNOFF - INTENSITIES - INCHES PER HOUR
0.6
0.5
0.4
0.3
0.2
0.1
0
1.20"
1.20"
4 A.M. 5 6 7 8 9 10 11 NOON E.W.T. 1 2 3
DEC. 27, 1942.

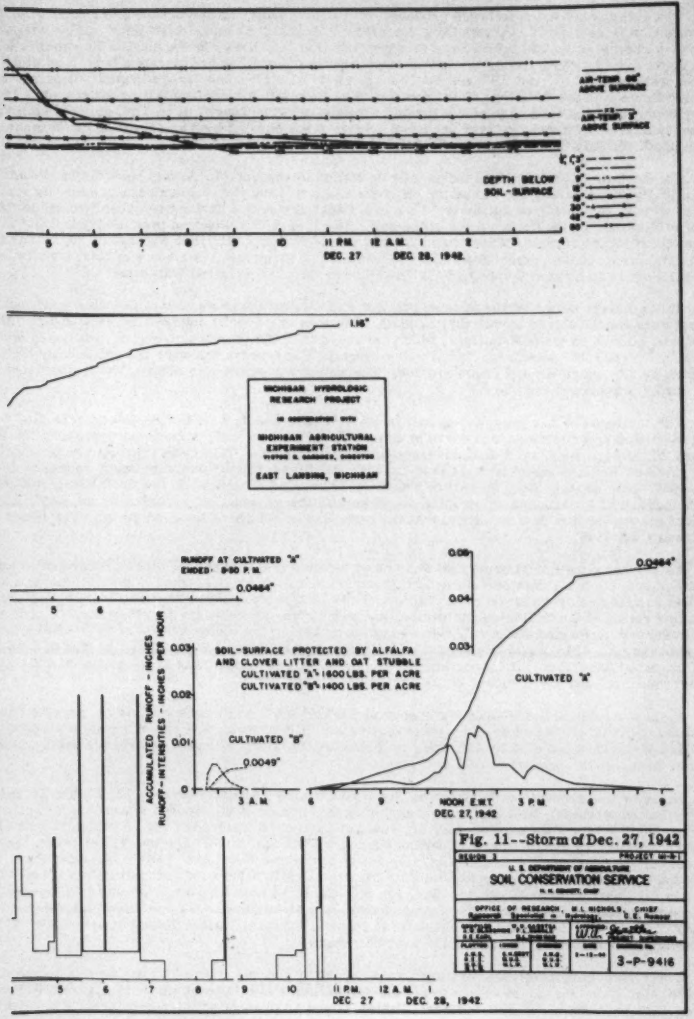

AIR-TEMP. 60" ABOVE SURFACE
AIR-TEMP. 3" ABOVE SURFACE
DEPTH BELOW SOIL-SURFACE
5 6 7 8 9 10 11 P.M. 12 A.M. 1 2 3 4
DEC. 27 DEC. 28, 1942.
1.16"
MICHIGAN HYDROLOGIC RESEARCH PROJECT
IN COOPERATION WITH
MICHIGAN AGRICULTURAL EXPERIMENT STATION
EAST LANSING, MICHIGAN
RUNOFF AT CULTIVATED "A" ENDED 8:30 P.M.
0.0464"
SOIL-SURFACE PROTECTED BY ALFALFA AND CLOVER LITTER AND OAT STUBBLE
CULTIVATED "A" 1800 LBS. PER ACRE
CULTIVATED "B" 1400 LBS. PER ACRE
CULTIVATED "B"
0.0049"
CULTIVATED "A"
0.0464"
ACCUMULATED RUNOFF - INCHES
RUNOFF - INTENSITIES - INCHES PER HOUR
0.03
0.02
0.01
0
0.08
0.04
3 A.M. 6 9 NOON E.W.T. 3 P.M. 6 9
DEC. 27, 1942
5 6 7 8 9 10 11 P.M. 12 A.M. 1
DEC. 27 DEC. 28, 1942.

Fig. 11--Storm of Dec. 27, 1942

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SOIL CONSERVATION SERVICE

3-P-9416

The rainstorms which followed produced very little runoff. Rain amounting to a total of 0.76 inch fell on December 26. At this time there was no frost in the soil. Snow-depth, of course, decreased rapidly under the influence of this precipitation. As shown in Figure 10, the runoff did not begin until five hours after the rain started. Furthermore, the hydrographs from both cultivated watersheds "A" and "B" are not characteristic of the summer type of runoff. The water comes through in one definite and sustained peak of flow with a very long falling-stage, since this flow consists of the discharge of a saturated snow-layer. The runoff, of course, did not begin until supersaturation of the snow-layer occurred. Seventy-six one-hundredths of an inch (0.76 inch) of rain produced only 0.0062 inch of runoff at Cultivated Watershed "A".

As shown in Figure 11, 1.16 inches of rain fell on December 27. At this time the snow had practically disappeared, air-temperatures were about 40°, but the soil-temperatures in the surface-horizon remained not far above 32°, a great deal of the heat having been absorbed as latent heat of fusion in taking the frost out of the soil. The 1.16-inch rainstorm produced only 0.0049 inch of runoff at Cultivated Watershed "B" and 0.0464 inch at Cultivated Watershed "A". For the two rainstorms of December 26 and 27, 1942, totaling 1.92 inches, the amount of total runoffs were 0.0111 inch at Cultivated Watershed "B" and 0.0540 inch at Cultivated Watershed "A".

These charts show how the thawing out of the soil under the protection of the snowbank made it possible for the soil to absorb this rainfall. The flow was greatly impeded by snow and by litter and oats-stubble on the soil-surface, which amounted to 1,650 pounds per acre, at Cultivated Watershed "A", and 1,450 pounds at "B" (air dry weight). Flow-velocities were not sufficiently high to pick up soil-particles and cause erosion. The water was practically clear. The temperature of the runoff-waters was exactly 32°.

The inclusion in this progress-report of observations and data pertaining to one period of runoff at the cultivated watersheds will serve to illustrate the project's investigational approach. On February 26, 1944, a very rapid disappearance of snow took place. This runoff resulted in the rise in the stage of the Red Cedar River at East Lansing, Michigan, of four feet over night February 26 and 27, 1944. The Lansing State Journal of February 28 carried an article on the flood illustrated with a photograph of a marooned automobile, together with the information, released by the East Lansing United States Weather Bureau office, that the level was a foot above flood-stage for a few hours on February 27, 1944.

As the snow-melt of February 26 was one of the most rapid observed since this project's establishment, the basic data pertaining to this period of runoff are presented in detail to permit the reader to make analyses of his own. Tables 10 and 11 present antecedent conditions of precipitation and runoff at the cultivated and wooded watersheds during February 5 to February 27. The one snow-survey performed at the cultivated watersheds during the winter season of 1943-44 disclosed on February 22, 1944, water-equivalent of 1.40 inches at Cultivated Watershed "A" and of 0.98 inch at Cultivated Watershed "B", at 15^h00^m EWT. Average snow-depth was 4-1/2 inches at Cultivated Watershed "A" and 3-1/4 inches at Cultivated Watershed "B".

A snow-survey at the Wooded Watershed at 15^h30^m EWT on February 21, 1944, indicated an average depth of 4-1/4 inches and a water-equivalent of 0.90 inch. The one other survey at the Wooded Watershed made at 15^h30^m EWT on February 23, 1944, indicated an average depth of four inches with a water-equivalent of 1.10 inches.

No snow was present on February 5. Some runoff took place on February 22, 25, and 26 at the cultivated watersheds. No runoff occurred during this period at the Wooded Watershed. Figure 12 shows runoff taking place on February 23, 1944, at Cultivated Watershed "B". Tables 12 and 13 present similar information for the period February 27 to March 16. The watersheds were again without snow-cover on March 16. The information presented in the four Tables indicates that, presence of the mulch-layer notwithstanding, practically all of the rain and snowfall received during the period February 5 to March 16, 1944, ran off. Table 14 lists air-temperatures as recorded by the hygrothermograph at level of 66 inches above the soil-surface at the cultivated watersheds. Table 15 lists departures of air-temperatures from 32° and cumulative degree-hours above 32° for February 26 and 27, 1944, at the cultivated watersheds.

Table 16 presents soil-temperatures as recorded by the resistance-thermometer apparatus. Circuit No. 15 in this series refers to the air-temperature at this point shown in Figure 1 at the three-inch level above the soil-surface. Tables 17 and 18 present soil-temperatures as determined by the manually operated thermocouple potentiometer and resistances of the gypsum blocks, corrected to 60°F, at the time indicated. It is to be kept in mind that high resistances of gypsum blocks

Tables 10 and 11--Summary precipitation and runoff, cultivated and wooded watersheds, February 5-27, 1943

Date	Cultivated watersheds						Wooded watersheds			
	Precipitation[a]			Runoff			Precipitation[ad]			
	Kind	Recording	Standard	Shielded	"A"	"B"	Kind	Recording	Standard	Shielded
1943		in	in	in	in	in		in	in	in
Feb. 5	b	...	...	...	c	c	....	...	...	...
6	b	...	...	...	....	....	Snow	0.05	0.06	0.07
7	Snow	0.03	0.02	0.04	....	....	Snow	T	T	T
8	Snow	0.01	0.02	0.05	....	....	Snow	T	T	T
9	Snow	0.04	0.09	0.20	....	....	Snow	T	T	T
10	Snow	0.01	0.01	0.01	....	....	Snow	0.04	0.04	0.10
11	Snow	0.04	0.10	0.04	....	....	Snow	0.09	0.11	0.25
14	Snow	0.11	0.14	0.25	....	....	Snow	0.15	0.15	0.22
16	....	...	...	...	....	....	Snow	T	T	T
17	Snow	0.35	0.34	0.43	....	....	Snow	0.40	0.41	0.42
20	....	...	...	...	....	....	Snow	T	T	T
22	Rain	0.66	0.67	0.75	0.4940	0.5803	Rain	0.79	0.79	0.84
23	Snow	0.14	0.14	0.15	....	....	Snow	0.18	0.17	0.19
25	Rain	0.04	0.04	0.04	0.0281	0.0131	Rain	0.03	0.03	0.04
26	Rain	0.16	0.17	0.16	1.1164	1.2395	Rain	0.14	0.16	0.16
27	b	...	...	...	....	....	....	0.00	0.00	0.00
Totals		1.59	1.74	2.12	1.6385	1.8329	....	1.87	1.92	2.29

[a] Water-equivalent. [b] Soil bare; no snow. [c] Runoff from previous snow-layer not listed here. [d] No runoff at wooded watershed during February 6-27.

Tables 12 and 13--Summary precipitation and runoff, cultivated and wooded watersheds, February 27 to March 16, 1944

Date	Cultivated watersheds						Wooded watersheds			
	Precipitation[a]			Runoff			Precipitation[ac]			
	Kind	Recording	Standard	Shielded	"A"	"B"	Kind	Recording	Standard	Shielded
1944		in	in	in	in	in		in	in	in
Feb. 27	b	...	...	...	....	....	....	...	...	...
Mar. 2	Rain	T	T	T	....	....	....	...	...	...
3	Rain	0.09	0.11	0.15	0.0028	0.0142	Rain	0.07	0.09	0.09
4	Snow	0.02	0.02	0.02	....	....	Snow	0.02	0.02	0.02
5	Snow	T	T	T	....	....	Snow	T	T	T
6	Rain	0.03	0.03	0.05	0.0659	0.0567	Rain	0.07	0.07	0.09
7	Snow	0.03	0.03	0.05	....	....	Snow	0.02	0.03	0.03
8	Snow	T	T	T	....	....	Snow	T	T	T
9	Snow	T	T	T	....	....	Snow	T	T	T
10	Snow	T	T	T	....	....	Snow	T	T	T
11	Snow	T	T	T	....	....	Snow	T	T	T
12	Rain	0.23	0.22	0.24	0.1409	0.1631	Rain	0.22	0.22	0.24
13	....	...	...	...	....	....	....	0.00	0 00	0 00
14	Snow-rain	0.19	0.19	0.21	0.1297	0.1381	Snow-rain	0.17	0.17	0.18
15	Rain	0.52	0.52	0.58	0.2953	0.2664	Rain	0.36	0.35	0.38
16	Rain	0.08	0.08	0.09	0.2082	0.2289	Rain	0.15	0.15	0.15
Totals		1.19	1.20	1.39	.8428	.8574	....	1.08	1.10	1.18

[a] Water-equivalent. [b] Soil bare; no snow. [c] Runoff on wooded watershed as follows: March 15, 0.0159 inch; March 16, 0.0017 inch; total for the two days, 0.0176 inch.

Fig. 12--Runoff from snow taking place at Cultivated Watershed "B" February 23, 1944, at 14^h 08^m EWT [Rate of flow is 0.007 cubic foot per second, 0.0054 inch per hour; watershed area seen through flume; no visible indication on snow-surface of occurrence of this runoff (Photograph by W. U. Garstka)]

Fig. 13--Snow-melt runoff at Cultivated Watershed "A" on February 26, 1944, at 15^h 05^m EWT [Rate of runoff 0.264 cubic foot per second, 0.1323 inch per hour; flow is clear; protective layer of alfalfa, clovers, and grasses mulch having a density of 2,500 pounds per acre (air-dry weight) prevented erosion; runoff water tinted very light brown due to leaching from this organic matter (Photograph by W. U. Garstka)]

Table 14--Air-temperature data[a] by hygrothermograph cultivated watershed, February 26-27, 1944

Date	Time, EWT	Temper-ature	Date	Time, EWT	Temper-ature
1943	h m	°F	1943	h m	°F
Feb. 26	00 00	34	Feb. 27	01 00	39 1/2
	01 00	34 1/2		02 00	38
	02 00	34		03 00	37 1/2
	03 00	34		04 00	37
	04 00	34		05 00	37
	05 00	35		06 00	36
	06 00	35 1/2		07 00	35
	07 00	36		08 00	35
	08 00	36 1/2		09 00	34 1/2
	09 00	37		10 00	34
	10 00	39		11 00	34
	11 00	40		12 00	33 1/2
	12 00	42		13 00	33
	13 00	46		14 00	33
	14 00	51		15 00	32 1/2
	15 00	60		16 00	32
	16 00	63		17 00	32
	17 00	62 1/2		18 00	31 1/2
	18 00	61		19 00	31
	19 00	57		20 00	30 1/2
	20 00	54		21 00	30
	21 00	45		22 00	29 1/2
	22 00	40 1/2		23 00	29
	23 00	43		24 00	28 1/2
	24 00	41			

[a]Recording element located 66 inches above soil-surface.

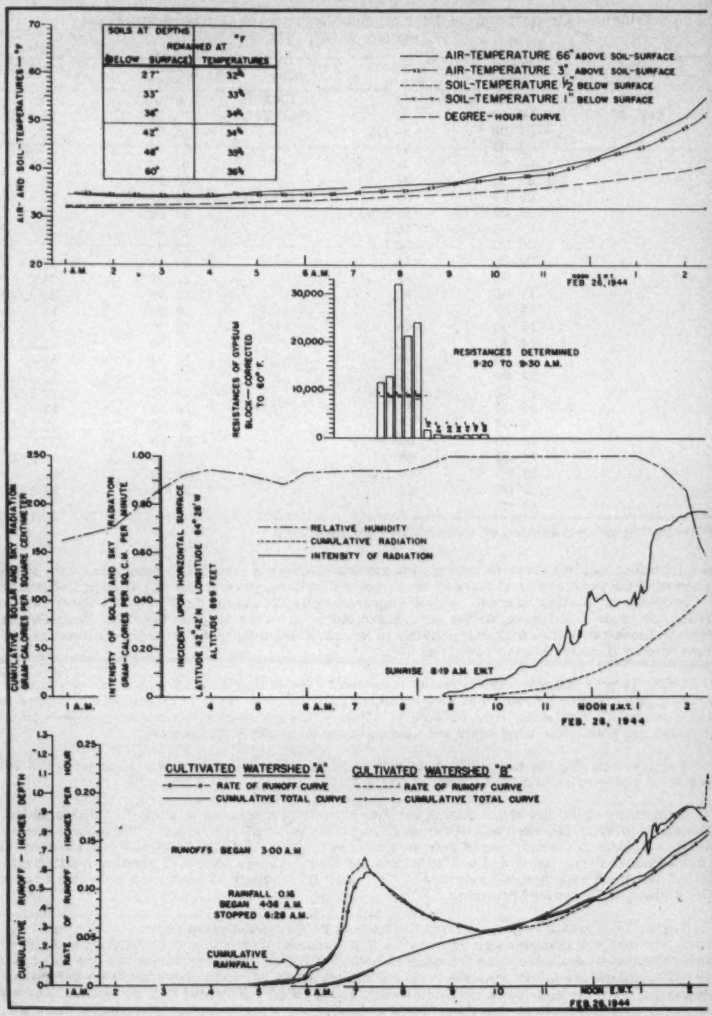
in a frozen soil do not serve to indicate the amount of water present. The blocks are very valuable in showing the presence or absence of frost, since a soil-temperature of 32° does in itself indicate the presence or absence of frost. A soil-temperature of 32° may prevail in a soil which has just frozen, or is about to freeze, or has just thawed out or is on the verge of thawing. The value of gypsum-block resistance makes it possible to interpret accurately the presence or absence of frost when soil-temperatures remain at 32°.

Table 19 presents wind-velocities as recorded by the United States Weather Bureau at East Lansing, Michigan, at a level of 90 feet above the soil-surface. This Table shows that during the major period of snow-melt, from 09^h00^m to 15^h00^m, the wind-velocity remained between 10 and 11 miles per hour. The wind continued blowing from the south and southeast.

Relative humidity for the period February 25 to 26 as recorded by a hair-element at the 66-inch level above soil-surface, is given in Table 20.

Cumulative solar and sky radiation for February 26 is presented in Table 21. Table 22 lists intensities of solar and sky radiation in gram-calories per cm^2 per minute. Table 23 is a record of the rainstorm of the morning of February 26, 1944, which totaled 0.16 inch. Peak-intensity for a one-minute interval amounted to 1.20 inches per hour. Tables 24 and 25 present detailed information of the runoff at cultivated watersheds "A" and "B". Figure 13 shows the snow-melt runoff taking place at Cultivated Watershed "A".

Figure 14 presents in graphic form the tabulated observation given above. At the top of the chart, air- and soil-temperature information is presented. The soil at the depth of one-half inch must have thawed out some time previous to 14^h30^m EWT on February 26. It is to be noted that the soil-temperature in the one-inch level did not get above 32° until about 20^h30^m whereas the determination of gypsum-block resistance made about 16^h00^m indicated that the soil was thawed out at the one-inch depth at that time. Soils at depths below the surface of two, three, four, six, nine, 12, 15, 18, and 21 inches remained at 32° throughout the period charted. Gypsum-block resistances determined at about 09^h30^m and those at about 16^h00^m indicate that the soil was


SOILS AT DEPTHS BELOW SURFACE
REMARKED AT °F TEMPERATURES
2.7"
3.3"
3.6"
4.2"
4.8"
6.0"
AIR-TEMPERATURE 66" ABOVE SOIL-SURFACE
AIR-TEMPERATURE 3" ABOVE SOIL-SURFACE
SOIL-TEMPERATURE ½" BELOW SURFACE
SOIL-TEMPERATURE 1" BELOW SURFACE
DEGREE-HOUR CURVE
AIR- AND SOIL-TEMPERATURES — °F
FEB 28, 1944
RESISTANCES OF GYPSUM BLOCKS CORRECTED TO 60° F.
RESISTANCES DETERMINED 9-20 TO 9-30 A.M.
CUMULATIVE SOLAR AND SKY RADIATION GRAM-CALORIES PER SQUARE CENTIMETER
INTENSITY OF SOLAR AND SKY RADIATION GRAM-CALORIES PER SQ.C.M. PER MINUTE
INCIDENT UPON HORIZONTAL SURFACE
LATITUDE 42°42'N LONGITUDE 84°28'W
ALTITUDE 899 FEET
RELATIVE HUMIDITY
CUMULATIVE RADIATION
INTENSITY OF RADIATION
SUNRISE 6:19 A.M. E.W.T.
NOON E.W.T.
FEB. 28, 1944
CULTIVATED WATERSHED "A"
RATE OF RUNOFF CURVE
CUMULATIVE TOTAL CURVE
CULTIVATED WATERSHED "B"
RATE OF RUNOFF CURVE
CUMULATIVE TOTAL CURVE
CUMULATIVE RUNOFF — INCHES DEPTH
RATE OF RUNOFF — INCHES PER HOUR
RUNOFFS BEGAN 3:00 A.M.
RAINFALL 0.16
BEGAN 4:36 A.M.
STOPPED 6:28 A.M.
CUMULATIVE RAINFALL
NOON E.W.T.
FEB 28, 1944

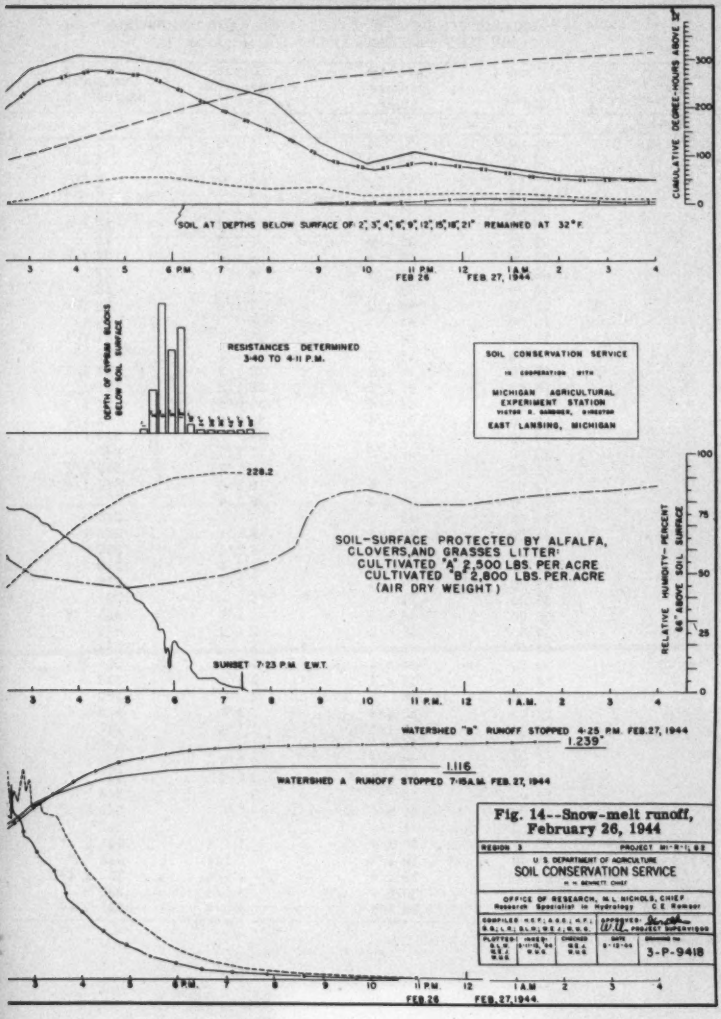

CUMULATIVE DEGREE-HOURS ABOVE 32°
300
200
100
0
SOIL AT DEPTHS BELOW SURFACE OF 2", 3", 4", 6", 9", 12", 15", 18", 21" REMAINED AT 32°F.
3 4 5 6 P.M. 7 8 9 10 11 P.M. FEB. 26 12 1 A.M. FEB. 27, 1944 2 3 4
DEPTH OF GYPSUM BLOCKS BELOW SOIL SURFACE
RESISTANCES DETERMINED 3-40 TO 4-11 P.M.
SOIL CONSERVATION SERVICE
IN COOPERATION WITH
MICHIGAN AGRICULTURAL EXPERIMENT STATION
VICTOR R. GARDNER, DIRECTOR
EAST LANSING, MICHIGAN
228.2
SOIL-SURFACE PROTECTED BY ALFALFA, CLOVERS, AND GRASSES LITTER:
CULTIVATED "A" 2,500 LBS. PER ACRE
CULTIVATED "B" 2,800 LBS. PER ACRE
(AIR DRY WEIGHT)
SUNSET 7:23 P.M. E.W.T.
RELATIVE HUMIDITY-PERCENT 64" ABOVE SOIL SURFACE
100
75
50
25
0
3 4 5 6 7 8 9 10 11 P.M. 12 1 A.M. 2 3 4
WATERSHED "B" RUNOFF STOPPED 4-25 P.M. FEB. 27, 1944
1.239"
1.116
WATERSHED A RUNOFF STOPPED 7-15 A.M. FEB. 27, 1944
3 4 5 6 P.M. 7 8 9 10 11 P.M. FEB. 26 12 1 A.M. FEB. 27, 1944 2 3 4

Fig. 14--Snow-melt runoff, February 26, 1944

REGION 3 PROJECT SH-R-1, 62

U. S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE
H. H. BENNETT, CHIEF

OFFICE OF RESEARCH, M. L. NICHOLS, CHIEF
Research Specialist in Hydrology C. E. Ramser

COMPILED: H.C.F., A.G.S., H.F.; G.L.L., G.L.H., O.E.J., C.O.G. APPROVED: W. C. [illegible] PROJECT SUPERVISOR

PLOTTED:	INKED:	CHECKED	DATE	Drawing No.
G.L.H.	G.L.H., O.E.J.	H.C.F.	5-12-44	3-P-9418
O.E.J.	H.C.F.	A.G.S.		
H.C.F.	A.G.S.	H.C.F.		

Table 15--Degree-hours above 32°F at 66 inches above soil-surface, cultivated watershed, February 26-27, 1944

Date	Time ending EWT	Average temperature	Departure from 32°F	Cumulative degree-hours
1944	h m	°F	°F	
Feb. 26	01 00	34 1/4	2 1/4	2 1/4
	02 00	34 1/4	2 1/4	4 1/2
	03 00	34	2	6 1/2
	04 00	34	2	8 1/2
	05 00	34 1/2	2 1/2	11
	06 00	35 1/4	3 1/4	14 1/4
	07 00	35 3/4	3 3/4	18
	08 00	36 1/4	4 1/4	22 1/4
	09 00	36 3/4	4 3/4	27
	10 00	38	6	33
	11 00	39 1/2	7 1/2	40 1/2
	12 00	41	9	49 1/2
	13 00	44	12	61 1/2
	14 00	48 1/2	16 1/2	78
	15 00	55 1/2	23 1/2	101 1/2
	16 00	61 1/2	29 1/2	131
	17 00	62 3/4	30 3/4	161 3/4
	18 00	61 3/4	29 3/4	191 1/2
	19 00	59	27	218 1/2
	20 00	55 1/2	23 1/2	242
	21 00	49 1/2	17 1/2	259 1/2
	22 00	42 3/4	10 3/4	270 1/4
	23 00	41 3/4	9 3/4	280
	24 00	42	10	290
Feb. 27	01 00	40 1/4	8 1/4	298 1/4
	02 00	38 3/4	6 3/4	305
	03 00	37 3/4	5 3/4	310 3/4
	04 00	37 1/4	5 1/4	316
	05 00	37	5	321
	06 00	36 1/2	4 1/2	325 1/2
	07 00	35 1/2	3 1/2	329
	08 00	35	3	332
	09 00	34 3/4	2 3/4	334 3/4
	10 00	34 1/4	2 1/4	337
	11 00	34	2	339
	12 00	33 3/4	1 3/4	340 3/4
	13 00	33 1/4	1 1/4	342
	14 00	33	1	343
	15 00	32 3/4	0 3/4	343 3/4
	16 00	32 1/4	0 1/4	344
	17 00	32	0	344
	18 00	31 3/4	- 1/4	343 3/4[a]
	19 00	31 1/4	- 3/4	343[a]
	20 00	30 3/4	- 1 1/4	341 3/4[a]
	21 00	30 1/4	- 1 3/4	340[a]
	22 00	29 3/4	- 2 1/4	337 3/4[a]
	23 00	29 1/4	- 2 3/4	335[a]
	24 00	28 3/4	- 3 1/4	331 3/4[a]

[a] Algebraic total.

Table 16--Temperatures by resistance-thermometer recorder, profile "A", cultivated watersheds, February 26, 1944

Time	Depth in inches; circuit														
	1/2:1	1:2	2:3	4:4	6:5	-:6	1:7[c]	10:8	12:9	15:10	18:11	21:12	27:13	33:14	3:15[a]
h m, h m	°F	°F	°F	°F	°F	°F	°F	°F	°F	°F	°F	°F	°F	°F	°F
23 58-00 13	32	32	32	32	32	..	32	32	32	32	32	32	32 3/4	33 3/4	34 1/4
00 58-01 13	32	32	32	32	32	..	32	32	32	32	32	32	32 3/4	33 3/4	34 1/2
01 58-02 13	32	32	32	32	32	..	32	32	32	32	32	32	32 3/4	33 3/4	34 1/2
02 58-03 13	32	32	32	32	32	..	32	32	32	32	32	32	32 3/4	33 3/4	34
04 00-04 15	32	32	32	32	32	..	32	32	32	32	32	32	32 3/4	33 3/4	34 1/2
05 02-05 17	32	32	32	32	32	..	32	32	32	32	32	32	32 3/4	33 3/4	34 1/2
06 03-06 18	32	32	32	32	32	..	32	32	32	32	32	32	32 3/4	33 3/4	34 3/4
07 03-07 18	32	32	32	32	32	..	32	32	32	32	32	32	32 3/4	33 3/4	35 1/4
08 04-08 19	32	32	32	32	32	..	32	32	32	32	32	32	32 3/4	33 3/4	35 1/2
08 54-09 09	32	32	32	32	32	..	32	32	32	32	32	32	32 3/4	33 3/4	37 1/4
09 55-10 10	32	32	32	32	32	..	32	32	32	32	32	32	32 3/4	33 3/4	38
10 56-11 11	32	32	32	32	32	..	32	32	32	32	32	32	32 3/4	33 3/4	39
11 57-12 12	32	32	32	32	32	..	32	32	32	32	32	32	32 3/4	33 3/4	42 1/2
12 59-13 14	32	32	32	32	32	..	32	32	32	32	32	32	32 3/4	33 3/4	45
14 00-14 15	32	32	32	32	32	..	32	32	32	32	32	32	32 3/4	33 3/4	....
15 00-15 15	32 3/4	32	32	32	32	..	32	32	32	32	32	32	32 3/4	33 3/4	....
16 05-16 20	36	32	32	32	32	..	32	32	32	32	32	32	32 3/4	33 3/4	60
17 05-17 20	37 1/4	32	32	32	32	..	32	32	32	32	32	32	32 3/4	33 3/4	59
17 52-18 07	37 1/4	32	32	32	32	..	32	32	32	32	32	32	32 3/4	33 3/4	56
18 54-19 09	36	33	32	32	32	..	32	32	32	32	32	32	32 3/4	33 3/4	51
19 55-20 10	35	33	32	32	32	..	32	32	32	32	32	32	32 3/4	33 3/4	47
20 55-21 10	35 1/2	33	32	32	32	..	32	32	32	32	32	32	32 3/4	33 3/4	41 1/4
21 56-22 11	33 1/2	32	32	32	32	..	32	32	32	32	32	32	32 3/4	33 3/4	39
22 57-23 12	34	32 1/2	32	32	32	..	32	32	32	32	32	32	32 3/4	33 3/4	40 3/4

[a] No. 15 in air three inches above soil-surface. [b] Record of February 25, 1944.
Note: Circuit 16 not used. [c] One-inch depth at profile "B".

Table 17--Soil-temperatures and gypsum-block resistances, profile "A", February 26-27, 1944

Depth element	February 26, 1944				February 27, 1944	
	09[h]20[m]- 09[h]30[m], EWT		15[h]40[m]-16[h] 11[m], EWT		11[h]05[m]- 11[h]16[m], EWT	
	Temperature	Resistance[a]	Temperature	Resistance[a]	Temperature	Resistance[a]
	°F		°F		°F	
1/2	31.5		32		33	
1	31.5	11,600	31.5	610	32.5	515
3	31.5	12,800	31.5	9,000	32	445
6	31.5	32,000	31.5	27,000	32	14,500
9	31.5	21,200	31.5	17,200	32	8,000
12	31.5	24,000	31.5	22,100	32	15,900
18	31.5	1,830	31.5	1,720	32	1,550
24		650		625		625
30	32.5	545	32.5	570	33	550
36		520		520		545
42	34.5	595	33.5	495	34.5	595
48		680		660		690
60	37	790	36.5	680	37	805

[a] Corrected to 60°F.

Table 18--Soil-temperatures and gypsum-block resistances, profile "B", February 26-27, 1944

Depth element	February 26, 1944				February 27, 1944	
	09^h20^m-09^h30^m, EWT		15^h40^m-16^h11^m, EWT		11^h05^m-11^h16^m, EWT	
	Temperature	Resistance[a]	Temperature	Resistance[a]	Temperature	Resistance[a]
	°F		°F		°F	
1/2			61 3/4			
1	32	6,400	31.5	3,850	32.5	520
3	32	17,500	31.5	16,500	32.25	4,500
6	32	40,000	31	35,000	32	13,700
9	32	10,500	31	9,800	32	5,700
12	32	4,950	31	4,800	32	4,450
18	32	660	31 1/2	660	32	610
24		740		740		630
30	33	665	32	660	33	605
36		635		645		620
42		610		625		640
48		695		725		690
60	36	750	35	670	36.5	735

[a] Corrected to 60°F.

Table 19--Wind-velocities[a], February 26-27, 1944

Time EWT	Direction	Wind-velocity	Time EWT	Direction	Wind-velocity
h m		mph			
02 00	SE	16	14 00	SE	10
03 00	SE	17	15 00	S	11
04 00	SE	15	16 00	SW	17
05 00	SE	15	17 00	SW	17
06 00	SE	16	18 00	SW	14
07 00	SE	18	19 00	SW	13
08 00	SE	16	20 00	SW	12
09 00	SE	11	21 00	W	14
10 00	SE	10	22 00	SW	11
11 00	SE	11	23 00	SW	12
12 00	S	11	24 00	SW	14
13 00	S	11	01 00	SW	14

[a] Recorded at U. S. Weather Bureau, East Lansing, Michigan, about 2 1/2 miles north-northwest of the cultivated watersheds; anemometer located 90 feet above soil-surface.

definitely frozen at a depth of 12 inches, that the frost was penetrating the 18-inch level, and that no frost existed at the 24-inch level and below. Temperatures remained at 32-3/4° for depth of 27 inches, at 33-3/4° for depth of 33 inches, at 34-1/4° for depths of 36 and 42 inches, at 35-1/2° for depth of 48 inches, and at 36-1/2° for depth of 60 inches. The stability of temperature in the soil-horizons indicates that a negligible amount of heat was supplied by the soil to assist in producing the recorded snow-melt.

Figure 15 is a curve used in converting readings of gypsum-block resistances to soil-moisture in per cents. A similar curve is available for each of 39 blocks. All the blocks were calibrated individually in hardware-cloth baskets containing samples of 800 to 1000 grams of the soil in which they are now placed in the field so that a separate conversion-curve is available for each individual block. Taking into account volume-weight data, it is possible to convert the percentage of moisture of a block to inches of depth of water present in the soil per inch depth of soil. For Block No. 36 (at the one-inch depth) the observed resistance of 610 ohms corresponds to soil-moisture content of 19.3 per cent on an oven-dry basis. This amounts to 0.25 inch of water depth per inch of soil depth. Gypsum-block readings indicate that at 16^h00^m the soil at the three-inch depth remained frozen. Observations made in the field at the time indicated that at 15^h30^m the soil had thawed out from the surface down to depths of 1-1/4 to 1-1/2 inches.

Table 20--Humidity[a] by hygrothermograph, cultivated watershed, February 25-26, 1944

Date	Time EWT	Humidity	Date	Time EWT	Humidity
	h m	pct		h m	pct
Feb. 26	01 00	65[b]	Feb. 26	22 00	84[c]
	02 00	70		23 00	78
	02 30	77		24 00	78[b]
	03 00	86	Feb. 27	01 00	81
	04 00	94[c]		02 00	83
	05 00	90		03 00	84
	05 30	88[b]		04 00	86
	06 00	93		05 00	87
	07 00	94		06 00	86
	08 00	94		07 00	89[c]
	09 00	100[c]		08 00	86
	10 00	100		09 00	85
	11 00	100		10 00	78
	12 00	100		11 00	70[b]
	13 00	100		12 00	76
	13 30	93		13 00	74
	14 00	86		14 00	74
	14 15	86		15 00	71
	14 30	55		16 00	73
	15 00	48		17 00	70
	16 00	45		18 00	73
	17 00	43[b]		19 00	72
	18 00	45		20 00	72
	19 00	48		21 00	71
	20 00	54		22 00	70
	20 30	60		23 00	71
	20 45	72		24 00	71
	21 00	79			

[a] Recording element located 66 inches above soil-surface. [b] Trough. [c] Peak.

Table 21--Cumulative solar and sky radiation, in gram-calories per square centimeter incident on a horizontal surface, February 26, 1944 (Eppley ten-junction pyrheliometer, Leeds and Northrup recording potentiometer; latitude 42° 42′ north; longitude, 84° 28′ west; elevation, 899 feet above sea-level)

Time EWT	Radiation	Cumulative radiation
h m	gram-calories per hour	
09 00	0.1	0.1
10 00	2.5	2.6
11 00	6.8	9.4
12 00	14.7	24.1
13 00	23.3	47.4
14 00	38.4	85.8
15 00	45.0	130.8
16 00	42.7	173.5
17 00	30.6	204.1
18 00	18.3	222.4
19 00	5.7	228.1
20 00	0.1	228.2
Total	228.2	....

Curves in the middle of Figure 14 show relative humidity, cumulative solar and sky radiation, and intensity of solar and sky radiation. The sudden emergence of a bright Sun at 13^h15^m was caused by the influx of a warmer air-mass. An examination of weather-map charts at the East Lansing, Michigan, office of the United States Weather Bureau disclosed an incipient influx of warm air. A clear continental air-mass began to express dominance at East Lansing shortly after noon of February 26, 1944. The lowermost curves on Figure 6 show rates and cumulative amounts of runoff at cultivated watersheds "A" and "B". It is interesting to note that at about 08^h00^m cumulative runoff at both of the watersheds amounted almost exactly to 0.16 inch, which was the amount of rainfall. The occurrence of this rain and the peaks of runoff at about 07^h15^m at both watersheds indicates that the snow in both watersheds was in a saturated condition incapable of holding any additional water. Following sunrise, air-temperatures increased shortly after the incidence of measurable quantities of solar and sky radiation and increased quantities of water began to run off. Rates of runoff for the period 10^h00^m to 14^h00^m are practically identical at the two watersheds. Unfortunately there was insufficient snow at the watersheds to continue supplying water for the runoff, almost all of the snow having disappeared by 16^h30^m.

Tables 26, 27, and 28 deal only with data from Cultivated Watershed "A". It is evident from the cumulative runoff-curves of the two cultivated watersheds, as shown in Figure 14, that a similar analysis of data for Cultivated Watershed "B" would result in ratios having similar numerical values. Table 26 presents an analysis of the principal sources of heat which produced this snow-melt. Taking into account solar and sky radiation alone, this Table shows that quantities of heat from two to 13 times the amount required to melt the snow were available.

There appears to be a close relationship between cumulative degree-hours above 32° and cumulative runoff for the period 10^h00^m to 14^h00^m. A similar analysis of other storms has produced degree-hour runoff-ratios which show a consistency for each period of snow-melt. The numerical values of this ratio show, however, considerable difference for different storms.

One of this project's ultimate objectives is that of evaluating a composite factor which can be practically applied with some degree of accuracy to make it possible to forecast the rates of snow-melt. The application of such a factor, coupled with snow-density data (which would have to be ascertained for a given snow-blanket at the desired time through snow-surveys or samplings) should make it possible to forecast yield of water

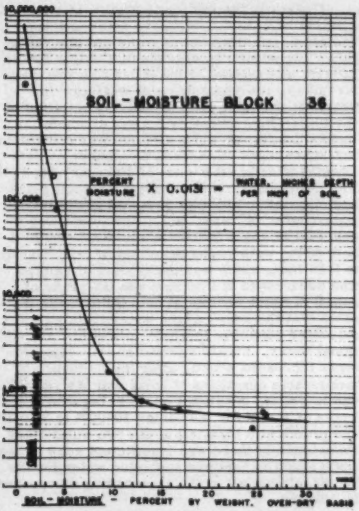

SOIL-MOISTURE BLOCK 36
PERCENT MOISTURE
X 0.013 =
WATER, INCHES DEPTH PER INCH OF SOIL
SOIL-MOISTURE - PERCENT BY WEIGHT, OVEN-DRY BASIS

Fig. 15--Relation to convert gypsum-block resistance to soil-moisture percentage

from snow-fields. An estimate of the quantity and characteristics of runoff which may be produced by this snow-yield would depend further upon the judicious application of knowledge of infiltration (related to a great extent upon the presence or absence of frost in the ground) and upon a knowledge of the hydraulics of the given stream-channel system.

In the combination of soil-temperature evaluating apparatus and gypsum blocks, the hydrologist hasat hand a technique of readily ascertaining the presence or absence of frost in the ground and of determining the exact thickness and position in the soil-profile of each frozen layer. Numerous samplings of soil with a soil-tube, sometimes called a geotome, have established the validity of the technique in soils which have an appreciable moisture-content at the time of freezing.

The principal sources of heat producing snow-melt are: Air-temperature, solar and sky radiation, and latent heat of vaporization released by the condensation of water-vapor. Heat supplied by the soil may be of importance in early fall in producing snow-melt, but it can be considered of negligible significance in contributing to snow-melt in the spring.

It may be of interest to note in Tables 27 and 28 that a somewhat consistent relationship appears between the composite value of degree-hours above 32° and solar-and-sky radiation and the amount of measured runoff. In the extreme right-hand column of Table 27, the average of the hourly values ending at 11^h to 15^h of the $[Y/(S/D)]$ ratio is 0.071. Deleting the values for the early morning hour ending at 10^h EWT (08^h09^m true solar time at the Pyrheliometric Station at East Lansing, Michigan) and for the hour ending at 15^h, when the snow-cover was disappearing, the average is 0.087. Values of solar and sky radiation incident upon a horizontal surface have been used in these computations, since, almost without exception, sustained records of pyrheliometric observations are based upon horizontal-surface instrumentation. Only a few stations in the country have the specialized equipment necessary for evaluating solar energy incident upon a surface at right-angles (normal) to the radiation. An expression relating to the physiographic characteristics of a given watershed will have to be considered in the composite snow-yield factor previously discussed.

Solar radiation in itself cannot be used as a direct criterion for estimating snow-melt, since it has been widely observed that, at air-temperatures below freezing, high intensities of solar radiation produce no visible snow-melt, provided that the snow is clean. The presence of soil-dust or soot may result in a considerably accelerated rate of compaction of the snow-layer. The ratios given for the snow-melt of February 26, 1944, should not be universally applied and are not being advanced as a proven hypothesis, but merely as one example of the effort to arrive at a simple index for snow-melt evaluation. In using such ratios in the computation of other periods of snow-melt, a tentatively infinitesimal value has been assigned to solar radiation when the air-temperature is below 32°. The composite ratio as given does not contain a factor for relative humidity. Neither does it as yet take into account any heat contributed by turbulence of air-masses at the snow-surface. It remains to be ascertained if it may be acceptable to think of this heat-source as contained in the degree-hour figure.

Table 22--Solar and sky radiation in gram-calories per square cm per minute, February 26, 1944

Time EWT	Radiation	Time EWT	Radiation	Time EWT	Radiation	Time EWT	Radiation
h m		h m		h m		h m	
08 48	0.000	11 42	0.226	14 24	0.767	17 06	0.408
08 54	0.015	11 48	0.295	14 30	0.763	17 12	0.378
09 00	0.020	11 54	0.300	14 36	0.758	17 18	0.369
09 06	0.020	12 00	0.442	14 42	0.758	17 24	0.344
09 12	0.020	12 06	0.398	14 48	0.758	17 30	0.320
09 18	0.029	12 12	0.408	14 54	0.753	17 36	0.295
09 24	0.034	12 18	0.418	15 00	0.743	17 42	0.251
09 30	0.039	12 24	0.398	15 06	0.728	17 48	0.251
09 36	0.054	12 30	0.378	15 12	0.714	17 54	0.089
09 42	0.054	12 36	0.393	15 18	0.694	18 00	0.211
09 48	0.064	12 42	0.389	15 24	0.689	18 06	0.182
09 54	0.069	12 48	0.398	15 30	0.674	18 12	0.162
10 00	0.069	12 54	0.403	15 36	0.664	18 18	0.147
10 06	0.073	13 00	0.393	15 42	0.645	18 24	0.078
10 12	0.073	13 06	0.442	15 48	0.634	18 30	0.064
10 18	0.084	13 12	0.453	15 54	0.615	18 36	0.054
10 24	0.098	13 18	0.629	16 00	0.610	18 42	0.054
10 30	0.123	13 24	0.698	16 06	0.595	18 48	0.054
10 48	0.123	13 30	0.703	16 12	0.585	18 54	0.039
10 54	0.147	13 36	0.709	16 18	0.565	19 00	0.024
11 00	0.162	13 42	0.718	16 24	0.546	19 06	0.020
11 06	0.182	13 48	0.738	16 30	0.527	19 12	0.015
11 12	0.221	13 54	0.753	16 36	0.516	19 18	0.015
11 18	0.172	14 00	0.753	16 42	0.492	19 24	0.015
11 24	0.202	14 06	0.763	16 48	0.472		
11 30	0.295	14 12	0.767	16 54	0.447		
11 36	0.316	14 18	0.767	17 00	0.428		

Table 23--Record of rainfall-intensity, cultivated watersheds, February 26, 1944
(Fergusson 9-inch rain-gage; latitude 42° 42′ 08″ north, longitude, 84° 28′ 29″ west; elevation, 888 feet above sea-level; NE 1/4, SW 1/4, Section 30, Township 4N, Range 1W)

Time	Interval	Accum. depth	Depth for		Intensity for	
			Each interval	Regular interval	Each interval	Regular interval
h m	min	in	in	in	in/hr	in/hr
04 36	0	.00	.00	. . .	0.00	. . .
04 37	1	.01	.01	. . .	0.60	. . .
05 38	61	.02	.01	. . .	0.01	. . .
05 45	7	.05	.03	. . .	0.26	. . .
05 47	2	.05	.00	. . .	0.00	. . .
05 48	1	.06	.01	. . .	0.60	. . .
05 49	1	.06	.00	. . .	0.00	. . .
05 50	1	.08	.02	. . .	1.20	. . .
05 55	5	.08	.00	. . .	0.00	. . .
05 56	1	.10	.02	. . .	1.20	. . .
06 11	15	.12	.02	. . .	0.08	. . .
06 21	10	.13	.01	. . .	0.06	. . .
06 28	7	.16	.03	. . .	0.26	. . .

Maximum depth (inch) and intensity (in) for selected time-intervals

Duration in minutes							
2	5	10	15	20	30	60	120
.02	.04	.06	.08	.08	.09	.14	.16
.60	.60	.36	.32	.24	.18	.14	.08

Table 24--Record of runoff, cultivated watershed "A", 1.981 acres, February 26-27, 1944

Time EWT	Instantaneous rates of runoff		Accum. runoff	Time EWT	Instantaneous rates of runoff		Accum. runoff
h m	s - f	in/hr	in	h m	s - f	in/hr	in
03 00	.000	.0000	0.0000	12 21	.234	.1172	0.4817
04 30	.001	.0004	0.0003	12 35	.264	.1323	0.5108
04 45	.002	.0011	0.0005	12 45	.280	.1403	0.5335
04 53	.005	.0023	0.0007	12 58	.296	.1483	0.5648
05 12	.007	.0037	0.0016	13 05	.313	.1568	0.5827
05 40	.011	.0053	0.0037	13 09	.313	.1568	0.5933
05 53	.014	.0072	0.0050	13 11	.264	.1323	0.5981
05 57	.019	.0093	0.0055	13 15	.296	.1483	0.6075
06 00	.023	.0117	0.0065	13 18	.330	.1653	0.6153
06 02	.029	.0144	0.0069	13 21	.330	.1653	0.6236
06 03	.035	.0174	0.0072	13 22	.313	.1568	0.6263
06 04	.029	.0144	0.0075	13 26	.330	.1653	0.6370
06 06	.035	.0174	0.0080	13 30	.330	.1653	0.6480
06 11	.041	.0204	0.0096	13 40	.347	.1738	0.6762
06 15	.047	.0236	0.0111	13 52	.365	.1829	0.7119
06 20	.047	.0236	0.0131	14 10	.365	.1829	0.7668
06 26	.054	.0270	0.0156	14 23	.347	.1738	0.8054
06 30	.061	.0306	0.0175	14 31	.330	.1653	0.8280
06 36	.077	.0384	0.0209	14 32	.403	.2019	0.8311
06 42	.094	.0471	0.0278	14 33	.365	.1829	0.8343
06 45	.113	.0566	0.0304	14 34	.347	.1738	0.8373
06 47	.123	.0616	0.0324	14 42	.330	.1653	0.8599
06 49	.134	.0671	0.0345	14 47	.313	.1568	0.8733
06 51	.156	.0782	0.0369	14 48	.296	.1483	0.8758
06 53	.168	.0842	0.0396	15 00	.280	.1403	0.9047
06 55	.181	.0907	0.0425	15 10	.249	.1247	0.9268
07 00	.207	.1037	0.0506	15 20	.234	.1172	0.9470
07 06	.220	.1102	0.0616	15 28	.220	.1102	0.9631
07 10	.220	.1102	0.0689	15 32	.207	.1037	0.9692
07 12	.234	.1172	0.0727	15 39	.194	.0972	0.9809
07 20	.234	.1172	0.0883	15 48	.168	.0842	0.9945
07 30	.220	.1102	0.1072	16 00	.145	.0726	1.0102
07 40	.207	.1037	0.1250	16 12	.123	.0616	1.0236
07 50	.194	.0972	0.1417	16 18	.113	.0566	1.0295
08 00	.181	.0907	0.1573	16 33	.094	.0471	1.0425
08 10	.168	.0842	0.1719	16 50	.077	.0384	1.0546
08 20	.156	.0782	0.1854	17 09	.061	.0306	1.0655
08 30	.145	.0726	0.1980	17 30	.047	.0236	1.0750
08 55	.134	.0671	0.2271	17 55	.035	.0174	1.0835
09 12	.123	.0616	0.2453	18 26	.023	.0117	1.0910
09 50	.113	.0566	0.2827	18 48	.019	.0093	1.0948
10 24	.123	.0616	0.3162	19 10	.014	.0072	1.0978
10 40	.134	.0671	0.3333	19 50	.011	.0053	1.1020
11 00	.145	.0726	0.3566	20 32	.007	.0037	1.1051
11 11	.156	.0782	0.3704	21 30	.005	.0023	1.1080
11 24	.168	.0842	0.3880	22 00	.005	.0023	1.1091
11 37	.181	.0907	0.4070	23 30	.002	.0011	1.1116
11 50	.194	.0972	0.4273	01 40	.002	.0011	1.1139
12 04	.207	.1037	0.4507	04 00	.0008	.0004	1.1158
12 15	.220	.1102	0.4703	07 15	.000	.0000	1.1164

Table 25--Record of runoff, cultivated watershed "B", 1.349 acres, February 26-27, 1944

Time EWT	Instantaneous rates of runoff		Accum. runoff	Time EWT	Instantaneous rates of runoff		Accum. runoff
h m	s - f	in/hr	in	h m	s - f	in/hr	in
03 00	.0000	.0000	0.0000	13 35	.220	.1618	0.6208
04 24	.0008	.0006	0.0004	13 46	.234	.1721	0.6514
05 00	.002	.0015	0.0011	14 00	.249	.1831	0.6928
05 20	.005	.0033	0.0019	14 03	.249	.1831	0.7020
05 52	.007	.0045	0.0040	14 23	.249	.1831	0.7630
06 00	.011	.0077	0.0048	14 25	.264	.1941	0.7693
06 06	.014	.0105	0.0057	14 26	.296	.2177	0.7728
06 10	.019	.0137	0.0065	14 26.5	.296	.2177	0.7746
06 16	.023	.0172	0.0080	14 28	.264	.1941	0.7799
06 20	.029	.0212	0.0093	14 29	.249	.1831	0.7830
06 26	.035	.0255	0.0117	14 33	.249	.1831	0.7952
06 30	.041	.0299	0.0135	14 34	.249	.1831	0.7983
06 33	.047	.0346	0.0151	14 35	.264	.1941	0.8014
06 36	.054	.0396	0.0170	14 36	.249	.1831	0.8045
06 40	.061	.0449	0.0198	14 43	.249	.1831	0.8259
06 43	.069	.0504	0.0220	14 44	.264	.1941	0.8290
06 44	.077	.0563	0.0231	14 45	.280	.2059	0.8323
06 46	.103	.0760	0.0233	14 48	.296	.2177	0.8429
06 47	.113	.0831	0.0246	14 50	.280	.2059	0.8500
06 48	.123	.0905	0.0260	14 51	.264	.1941	0.8533
06 49	.134	.0985	0.0276	14 54	.249	.1831	0.8627
06 50	.145	.1066	0.0293	14 55	.280	.2059	0.8659
06 54	.156	.1147	0.0367	14 57	.264	.1941	0.8726
07 06	.168	.1235	0.0605	14 59	.249	.1831	0.8789
07 12	.181	.1331	0.0733	15 00	.234	.1721	0.8819
07 16	.168	.1235	0.0819	15 07	.249	.1831	0.9026
07 23	.156	.1147	0.0958	15 13	.234	.1721	0.9204
07 34	.145	.1066	0.1161	15 30	.220	.1618	0.9677
07 41	.134	.0985	0.1281	15 36	.207	.1522	0.9834
07 54	.123	.0905	0.1486	15 39	.207	.1522	0.9910
08 08	.113	.0831	0.1689	15 54	.181	.1331	1.0267
08 24	.103	.0760	0.1901	16 08	.156	.1147	1.0556
08 49	.094	.0691	0.2203	16 22	.134	.0985	1.0805
09 12	.085	.0626	0.2455	16 38	.113	.0831	1.1047
09 46	.077	.0563	0.2792	16 56	.094	.0691	1.1275
09 55	.077	.0563	0.2876	17 15	.077	.0563	1.1474
10 26	.077	.0563	0.3167	17 34	.061	.0449	1.1634
10 58	.085	.0626	0.3484	17 53	.047	.0346	1.1760
11 17	.094	.0691	0.3692	18 15	.035	.0255	1.1870
11 36	.103	.0760	0.3922	18 42	.023	.0172	1.1966
11 54	.113	.0831	0.4161	19 25	.014	.0105	1.2065
12 06	.123	.0905	0.4335	20 26	.007	.0054	1.2146
12 17	.134	.0985	0.4508	23 38	.002	.0015	1.2255
12 27	.145	.1066	0.4679	01 00	.005	.0033	1.2288
12 36	.156	.1147	0.4845	02 32	.002	.0015	1.2325
12 52	.168	.1235	0.5163	06 30	.0008	.0006	1.2365
13 00	.181	.1331	0.5334	16 25	.000	.0000	1.2395
13 07	.194	.1427	0.5495				
13 20	.207	.1522	0.5815				

Table 26--Snow-melt runoff, cultivated watershed "A", February 26, 1944

Time, EWT	Cumulative runoff	Runoff for hour ending		Calories required	Gm-cal per cm^2 for hour ending	Solar and sky radiation for hour ending
(1)	(2)	(3)	(4)	(5)	(6)	(7)
h	in	in	m^3/ac*	millions		gm-cal/hr
09	0.2280	.....	...../.	.....	0.1	.....
10	0.2890	0.0610	6.27	50.2	2.5	101.2
11	0.3566	0.0676	6.95	55.6	6.8	275.2
12	0.4500	0.0934	9.60	76.8	14.7	594.9
13	0.5680	0.1180	12.13	97.0	23.3	942.9
14	0.7390	0.1710	17.58	140.6	38.4	1,553.9
15	0.9047	0.1657	17.03	136.3	45.0	1,821.1

Time, EWT	Ratio [(7)/(5)]	Air-temperature at hour	Cumulative degree-hours above 32°F	Degree-hours for hour ending	Ratio [(3)/(11)] for hour ending	Ratio [(2)/(10)]
	(8)	(9)	(10)	(11)	(12)	(13)
h		°F				
09	.....	37	27	....	.....	.....
10	2.02	39	33	6	0.0102	0.0088
11	4.95	40	40.5	7.5	0.0090	0.0088
12	7.74	42	49.5	9	0.0104	0.0091
13	9.72	46	61.5	12	0.0098	0.0092
14	11.05	51	78	16.5	0.0104	0.0095
15	13.36	60	101.5	23.5	0.0071	0.0089

*Cubic meters per acre

Table 27--Hourly snow-melt related to certain factors, cultivated watershed "A", runoff of February 26, 1944

EWT hour ending	Runoff for hour ending, Y	Gm-cal per cm^2 for hour ending, S	Degree-hours above 32°F for hour ending, D	Ratio (S/D)	Ratio [Y/(S/D)]
h	in				
10	0.0610	2.5	6	0.416	0.147
11	0.0676	6.8	7.5	0.908	0.075
12	0.0934	14.7	9	1.633	0.057
13	0.1180	23.3	12	1.942	0.061
14	0.1710	38.4	16.5	2.327	0.074
15	0.1657	45.0	23.5	1.915	0.086

Table 28--Cumulative snow-melt related to certain factors, cultivated watershed "A", runoff of February 26, 1944

EWT hour ending	Cumulative runoff[a] for hour ending, Y_c	Cumulative solar and sky radiation, S_c	Cumulative degree-hours above 32°F, D_c	Ratio (S_c/D_c)	Ratio $[Y_c/(S_c/D_c)]$
h	in	per cm^2			
10	0.1290	2.6	33	0.079	1.63
11	0.1966	9.4	40.5	0.232	0.85
12	0.3900	24.1	49.5	0.487	0.59
13	0.4080	47.4	61.5	0.771	0.53
14	0.5790	85.8	78	1.100	0.53
15	0.7447	130.8	101.5	1.286	0.58

[a]0.16 inch rainfall subtracted.

No attempt has been made here to discuss the somewhat extensive literature on the subject of snow-melt. This progress-report on the hydrology of farm lands under winter conditions of snow-cover and frozen soil has dealt with only a fraction of this project's data, since hydrologic observations are continued throughout the year.

Soil Conservation Service in cooperation with
Michigan Agricultural Experiment Station,
East Lansing, Michigan

DISCUSSION

R. W. GERDEL (U. S. Weather Bureau, Sacramento, California)--The increased emphasis which has been accorded to the study of snow in recent years makes this contribution by Mr. GARSTKA both appropriate and timely. Only through an increased knowledge of the thermodynamic processes which contribute to snow-melt and runoff can the economics of snow-water be evaluated. In the far West the reservoir-capacity of deep snow-mantles determines the agricultural and industrial economy of wide areas. In the Eastern States, such economy is more a matter of crop-protection, soil-moisture supplies, soil-erosion, and flood-control although the latter problem is also dominant in the West.

The problem of measuring single storm or total seasonal precipitation as snow is a difficult one. Mr. GARSTKA indicates that a precipitation-gage equipped with a NIPHER shield is capable of measuring winter precipitation with considerable accuracy but that the actual water-equivalent of a snow-blanket at any given time can only be determined by a snow-survey.

Although the NIPHER shield may serve well in areas of low winter precipitation as snow or where long intervals elapse between storms, such shields are mechanically unsuitable to areas where storms amounting to three to six feet of new snow may occur. A more open-type shield such as the ALTER shield has proven more satisfactory under such conditions.

That a seasonal snow-storage gage may give a satisfactory index to the water-equivalent of a seasonal snow-pack is indicated by the following data from the Cooperative Snow Research Laboratory at Soda Springs, California.

Date, inclusive	Measured precipitation		
	Average for three gages on snow-course	Snow-surveys	
		Depth	Water-equivalent
December, 1942-March, 1943	43.28 inches	78.5 inches	38.4 inches
December, 1943-March, 1944	26.21 inches	56.1 inches	25.9 inches

It is, of course, recognized that many factors may have contributed to coincidence in the close agreement shown by the above data for gages and snow-surveys. However, it is probable that where snow-blankets of only four to ten inches are measured, difficulty will be encountered in obtaining

representative samples. Where the snow-pack may be six to eight feet in depth slight errors are absorbed in the enormous volume of snow and water measured.

The agricultural and hydrologic significance of the thawing of the soil beneath a snow-mantle is very important. As reported by Mr. GARSTKA such thawing appears to have resulted, at least temporarily, in a perched water-table within the surface several inches of soil and above a more impermeable frozen horizon. This phenomenon of a soil-thawing beneath a snow-mantle has been observed in central Ohio and in the high Sierra (at altitudes of 7,000 feet). In the latter location, the soil had been frozen to a depth of six inches and was at a temperature of 27.5 F previous to the arrival of the permanent snow-pack.

It is interesting to note that at East Lansing the soils apparently were in a saturated condition, down to at least 60 inches, during the winter months. Any analysis of snow-melt-runoff problems must take into consideration the soil-priming condition which appears to be present during the winter. Such priming was also observed in the Central Sierra beneath deep snow-mantles. From the standpoint of soil-physics, does such continued saturation presume a greater water-holding or field-capacity during the winter months due to increased viscosity or does it represent a condition of accretion to soil-water supplies at a rate at least equivalent to a retarded percolation or interflow to natural drainage?

One highly important contribution to snow-research that may be derived from this paper is the fact that snow apparently does not reach the same density in the more humid eastern sections of the country as in the high-altitude, dryer portions of the West before active runoff begins. Data presented by Mr. GARSTKA indicate that rapid and almost complete melting of the snow at East Lansing, Michigan, must have occurred with a snow-pack density of 35 per cent or less. In the high Sierra no appreciable runoff begins until the pack approaches a density of 50 per cent. Such differences indicate that the thermodynamic solution of rapid rates of snow-melt may not be universally applicable.

It is hoped that more answers to the many problems involved in snow research will be forthcoming from the Michigan Hydrologic Research Project of the Soil Conservation Service and Michigan State College.

WALTER T. WILSON (U. S. Weather Bureau, Washington, D. C.)--Mr. GARSTKA has presented a well-documented hydrologic and meterologic biography of three small basins in southeastern Michigan for the three winter seasons ending in 1944. The topographic, cultural, and other features of the basin have been carefully described. The time-scale, so to speak, has been expanded for selected periods of rapid snow-melt. The organization and presentation have been so thorough, objective, and extensive that this paper will be referred to frequently for source-material.

Early in the paper, the normal precipitation at East Lansing is stated to be 30.52 inches. This is the mean annual value--the mean monthly totals for November, December, January, February, March, and April, respectively, are 2.28, 2.03, 1.78, 1.77, 2.43, and 2.77 inches.

In this paper it has been suggested that the validity of a precipitation-gage can be determined by the performance of a snow-survey. This must be emphatically denied, because the results of a snow-survey are influenced not only by the wind during each snowstorm, but also by the uncertain effects of drifting, evaporation, infiltration, lateral flow of melted snow, interception, condensation, and other causes of snow-movement during the long period prior to the snow-survey. The snow-survey is not only a sample of the areal distribution of snow at the time of the survey, but implicitly is a sample of the effects of these varied exposure factors over a large area.

It is regretted that the instrumentation did not include a precipitation-gage equipped with a modern flexible shield of ALTER type.

An element that might well have been included in the observations, particularly during periods of rapid melting, is the thermal quality of the snow.

Near the end of the paper appears a statement that two to 13 times the quantity of heat required for the melting observed was available. A complete heat-balance must include not only the heat absorbed by the snow (which is limited by its thermal quality) but also the heat lost by the snow, such as evaporation into dry air, turbulent exchange into cold air, long-wave black-body radiation, and reflected solar radiation. The albedo may vary from nearly 90 per cent with dry snow, to about 50 per cent with snow that is melting.

In Table 26 appears the unit of runoff of cubic meters per acre. By way of constructive criticism, it may be said that a cubic meter is nearly exactly 0.0008 of an acre-foot.

Near the end of the paper appears the expression $[Y/(S/D)]$, which is referred to as constant. If $[Y/(S/D)] = K$, $Y = (KS/D)$, thus implying an inverse relation between snow-melt and degree-days under conditions of uniform insolation.

Anticipating the wide use that hydrologists will make of the data in GARSTKA'S excellent paper, it should be recalled that the effects of topographic, vegetative, and other internal basin-characteristics often obscure or transcend external effects such as meteorological factors. Thus, caution should accompany the application of empirical relationships to areas different from the one for which they are established.

ROBERT E. HORTON (Voorheesville, New York)--This paper contains a large mass of well collected and coordinated data which is capable of supplying a basis for many lines of study and research. Complete discussion is therefore impracticable.

Some years ago, when acting as Consultant of the Department of Agriculture on upland flood-control, the writer came to the realization that there were many regions where not very much could be accomplished under summer conditions, especially where most flood-damage occurs as a result of winter and spring floods. This at once raised the question as to whether the application of certain procedures, such as grass-cover, mulching, snow-spreading, fall plowing, contouring, and the like, might not prove beneficial both agronomically and in flood-control under winter conditions. In attempting a study of the subject the writer and his associate consultants, Messrs. W. W. HORNER and L. K. SHERMAN, were confronted with the paucity of data with regard to hydrologic phenomena taking place within the soil and at the soil-surface under winter conditions, in particular under snow-cover and during the snow-melt. Various conclusions had been arrived at by the writer and others, based on meager data, but many points were not covered and the data were wholly inadequate to serve as a basis for broader studies required.

Accordingly the Research Division of the Soil Conservation Service was urged to undertake experiments and studies of winter hydrology in agricultural regions of the United States where this is important, in particular to get data to determine infiltration-capacity of frozen soil and soil under snow-cover, ground-water conditions and replenishment under winter conditions, and soil-moisture under winter conditions.

Some difficulty was experienced in selecting a locality suitable for such experimental studies. It should have (1) abundant snow, (2) soil not too impervious, (3) suitable winter temperature-conditions to provide alternate snow-cover and thawing, with consequent frequent opportunities for study of the required factors during different parts of the winter season. The establishment of the East Lansing Winter Hydrologic Experiment Station was indirectly the outcome of these preliminary investigations and recommendations.

The writer is pleased to see that the results thus far obtained have in general borne out conclusions tentatively reached on various points.

There are a few matters which seem to require brief discussion.

(1) The drainage-basins are small and the runoff as recorded is purely surface-runoff. In this region, as generally throughout the middle West, crops, such as winter wheat, depend to a large degree on winter storage of soil-moisture used in the subsequent growing season. The studies of soil-moisture at the East Lansing Station will, it is hoped, contribute greatly to our knowledge of the somewhat complex phenomena of the annual cycle of soil-moisture.

While the writer understands that the data contained in the paper do not represent all lines of data collected, he was disappointed to find nothing regarding ground-water levels, for the reason that ground-water levels are exceedingly valuable in determining infiltration-capacity under winter conditions and supply about the only available basis of determining times at which soil-moisture becomes saturated to field-moisture-capacity throughout the entire soil-column and accretion to the water-table begins.

In addition to their agricultural uses the writer believes that experimental data such as those collected at East Lansing may be of extremely great value in connection with various engineering problems, such as operation of reservoirs and power-plants, but to be of value for this purpose

records of ground-water level are needed in addition to the other data collected. Also they are useful in interpreting the differences between hydrologic conditions on the different drainage-basins. For example, the low winter runoff from the wooded area as compared with the open areas, cited in Mr. GARSTKA'S paper, seems necessarily to be chiefly the result of higher infiltration-capacity of the forest-soil, although some of it may be due to snow-interception by vegetation. To the extent that it is the result of higher infiltration-capacity of the forest-soil, it should be reflected in a greater volume of ground-water accretion under the forest-cover. As a result the difference in total runoff from forest and non-forested areas in a region like central Michigan may be much less than the difference in surface-runoff considered alone.

(2) Mr. GARSTKA remarks that snow-depths are in most cases so shallow as to restrict the efficient use of the Mount Rose snow-tube. This suggests a brief discussion of a method essentially like that which the writer has used for some 30 years in getting water-equivalents of shallow snow-cover.

The snow-tube is light galvanized iron, eight inches in diameter--the same as a standard rain-gage tube--and three or four feet long, with a thin cutter-ring on the inside at one end, as in the Mount Rose tube. The rest of the equipment consists of scales, which should weigh up to 20 or 25 pounds, and a light, short-handled shovel with a flat, sharp edge. It is convenient to have the end of the snow-tube opposite the cutter closed, but with one or more adequate openings or a stop-cock to permit egress of air when the tube is shoved down into the snow. After shoving the tube downward to the ground, the snow is dug away from one side and the edge of the shovel slipped under the open end of the tube nearest to the ground and the tube with its snow-content tipped over to one side and lifted out. If there is a little snow which has not been picked up by the tube or shovel it can be scraped up and put in the measuring tube.

Between observations the scales and shovel--handle foremost--are placed in the measuring can, strapped together with a shawl-strap having a handle, making a light, convenient package, carried with one hand from station to station. This method has the advantage of ready portability, visual access to the column from which the snow-sample was taken and a larger snow prism as compared with the usual type of samplers for deep snow, thus insuring greater accuracy.

(3) The observed differences between snow caught by the standard gage, gage with NIPHER shield and measured snow on the ground, confirms conclusions reached by the writer many years ago but shows that we still have with us the vexed problem of determining winter precipitation in northern regions with reasonable accuracy.

The writer has found that the use of a snow-board, situated preferably in a forest-glade where no drifting occurs, provides a simple and reliable means of determining precipitation as snow, but this method, of course, fails when the winter precipitation occurs partly as snow and partly as rain.

(4) The writer is pleased that radiation as well as temperature is observed. Admittedly, temperature-excess is not a perfect measure of rate of snow-melt. Temperature-data are, however, the only data usually available to the engineer and it is desirable that studies of snow-melt in relation to meteorological factors should be continued until some system of factors is derived which an engineer can use as a guide in interpreting temperature-excess data in relation to the disappearance of snow-cover.

For additional discussion by J. E. CHURCH and closing remarks, see page 1060.

THE AVERAGE LENGTH OF THE SEASON WITH SNOW-COVER OF VARIOUS DEPTHS IN NEW ENGLAND

Robert G. Stone

The general significance of a snow-cover as it affects many physiographical and ecological processes, and in human economy, is so well known that a review of the subject is hardly necessary here; but statistical material on the occurrence of snow-cover at various places is surprisingly meager in published sources. Records of the depth of precipitation in form of snow are abundantly available, of course, but they are not of such immediate practical utility as those of the depth of snow lying on the ground. Unfortunately there is no simple correlation between the two phenomena, a fact which becomes obvious upon even superficial observation. It has long been the custom in many meteorological services to observe and record the depth of snow lying, but there is a disinclination to publish or analyze the results owing to uncertainties about the reliability

of the observations. It is very difficult to obtain a representative measure of the snow-cover and few of the ordinary Weather Bureau stations are in a position thoroughly to cope with the problem within the means at their disposal. Drifting and other local influences will often render a single spot-reading of the depth quite meaningless for obtaining a general estimate for the vicinity. Even a system of sampling a number of neighboring spots calls for a large exercise of judgment on the part of the observer. These shortcomings, however, are really serious chiefly for studies of individual situations, such as comparisons on a given date, whereas the averaging of large numbers of observations tends to eliminate individual errors in so far as they have a random character. Systematic local influences can often be allowed for in considering averages, if something is known about the exposure of the station, the method of observation, and the conditions of weather, etc. Yet the majority of published studies of the distribution of snow lying restrict themselves to merely the duration regardless of depth; only in regions where the depth is a question of prime economic importance do we find it given intensive analysis, as in the Alpine and more northerly parts of Europe, and in the snow-surveys of limited areas in the United States.

In the United States and Canada even the duration of snow lying has been given but the sketchiest sort of discussion in climatological literature. In the West and to a lesser extent in the East special snow-surveys are annually made in certain mountain watersheds in order to forecast the water that will become available for irrigation and water-power. These use a special technique of measurement and the observations cannot be directly compared with those taken at ordinary Weather Bureau stations. A large proportion of the United States Weather Bureau stations of first and second order and its cooperating third-order climatological stations have recorded the snow-depth daily or twice a month for many years; but these observations have not been published except in small part. In 1936 the National Park Service engaged the writer to prepare climatic material to aid in planning the recreational development of winter sports in New York and New England. Skiing being the chief interest, and, adequate depth of snow in sufficient duration being the chief requisite for a skiing resort, we were immediately led to a study of the Weather Bureau snow-depth records. The manuscript files were loaned us for the purpose. Later the Blue Hill Meteorological Observatory continued the project. Two reports have been published so far, one outlining the methodology of the study with examples of the results, and the second making available in concise and practical form a large mass of the data with a preliminary analysis [R. G. STONE, The distribution of the average depth of snow on ground in New York and New England: (I) Method of study, Trans. Amer. Geophys. Union, pp. 486-492, 1938; (II) Curves of average depth and variabilities, Trans. Amer. Geophys. Union, pp. 672-692, 1940]. A considerable number of maps have been prepared which were not included in the latter paper, which is rather devoted to the statistics and curves on which the maps are based. The series of maps printed here is of particular general interest. It shows on a topographic base the average number of consecutive weeks per winter with two inches or more, five inches or more, ten inches or more, and 15 inches or more snow-cover, respectively.

The features of the distributions shown are readily evident upon a brief inspection; the effects of the Atlantic Ocean and of the topography apparently predominate. The only feature that was not anticipated is the absence of marked latitude-effect; for low elevations in northern New England (and New York) do not seem to have an appreciably longer snow-cover season than those in southern New England (and New York) if the narrow belt along the Atlantic Coast be disregarded. The differences in elevation produce by far the most part of the variation in snow-cover.

For proper interpretation of these maps it is necessary to consider several circumstances of the manner in which they were drawn. The original data being somewhat crude and subject to the errors of measurement and local influences, and the stations being too few and unequally distributed, no more than a very generalized view of the statistics would be warranted. The length of the snow-season of any given depth had to be read off from the curves of average depths computed for two-week intervals; hence several stages of smoothing and interpolation are involved in obtaining the season-length values, which in turn are rounded off in units of a week. With the scale of map used, the sparse net of stations permitted or required much room for judgment in locating the isopleths; a general relation of the season-length with elevation being quite apparent, it was deemed best to follow contours in placing the isopleths between stations. This gives the maps a perhaps quite false appearance of detailed accuracy since the small sinuosities of the contours are faithfully reproduced. This is a defensible procedure as long as no better guide is available, and a smoothing of the isopleths to run across the grain of the topography would certainly be further from the truth than following contours. It is the pattern of the lines that counts, not the exact correlations of given season-length with height above sea-level. The map is thus impressionistic. It at least serves well

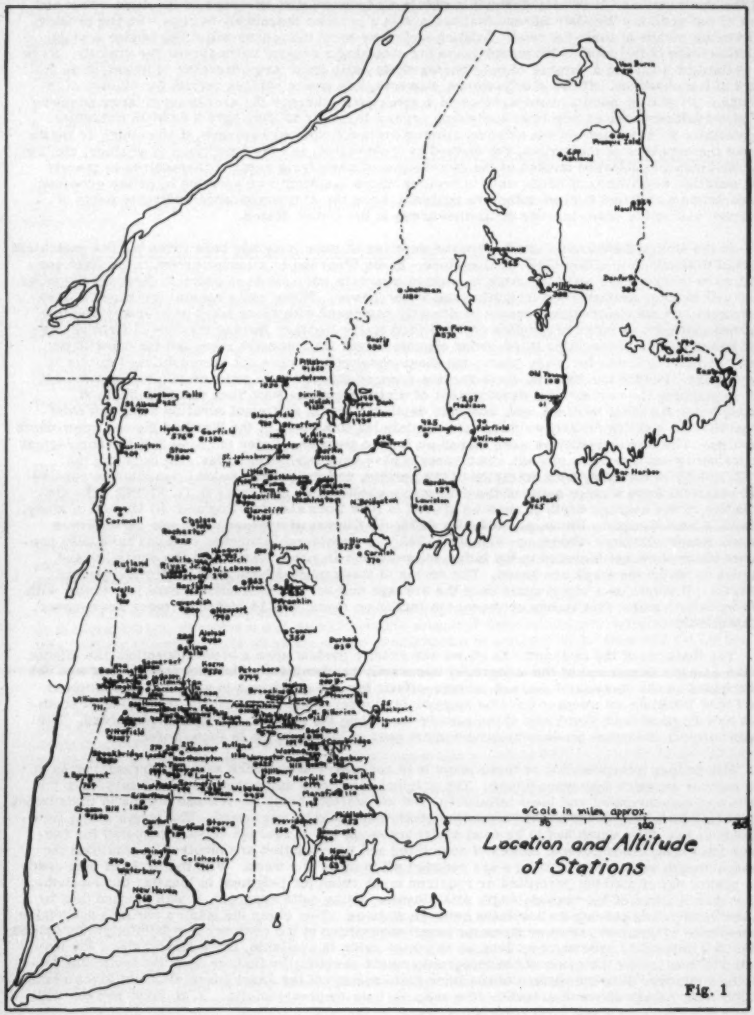


Fig. 1

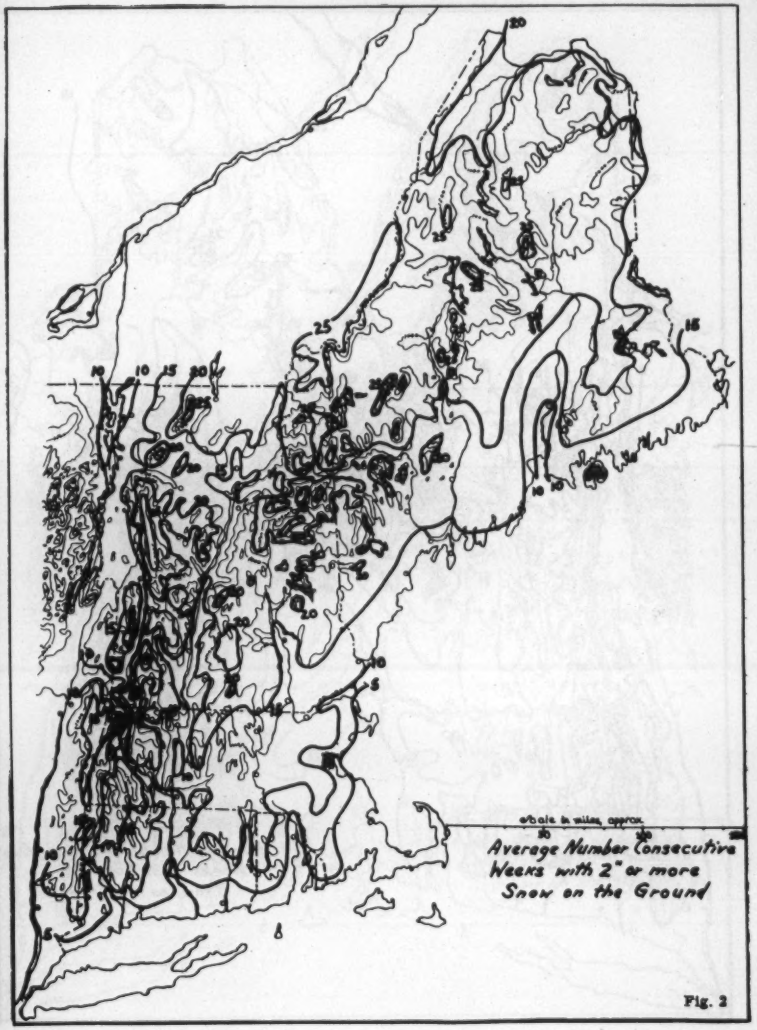

Scale in miles, approx.
Average Number Consecutive Weeks with 2" or more Snow on the Ground

Fig. 2

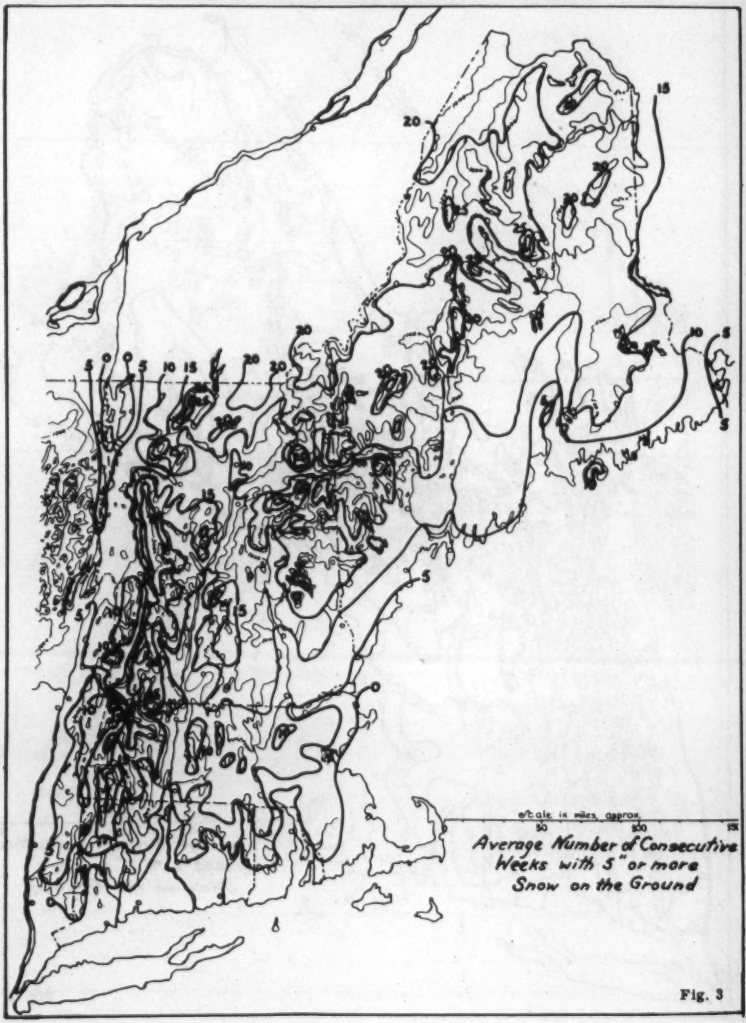

Average Number of Consecutive
Weeks with 5" or more
Snow on the Ground

Fig. 3

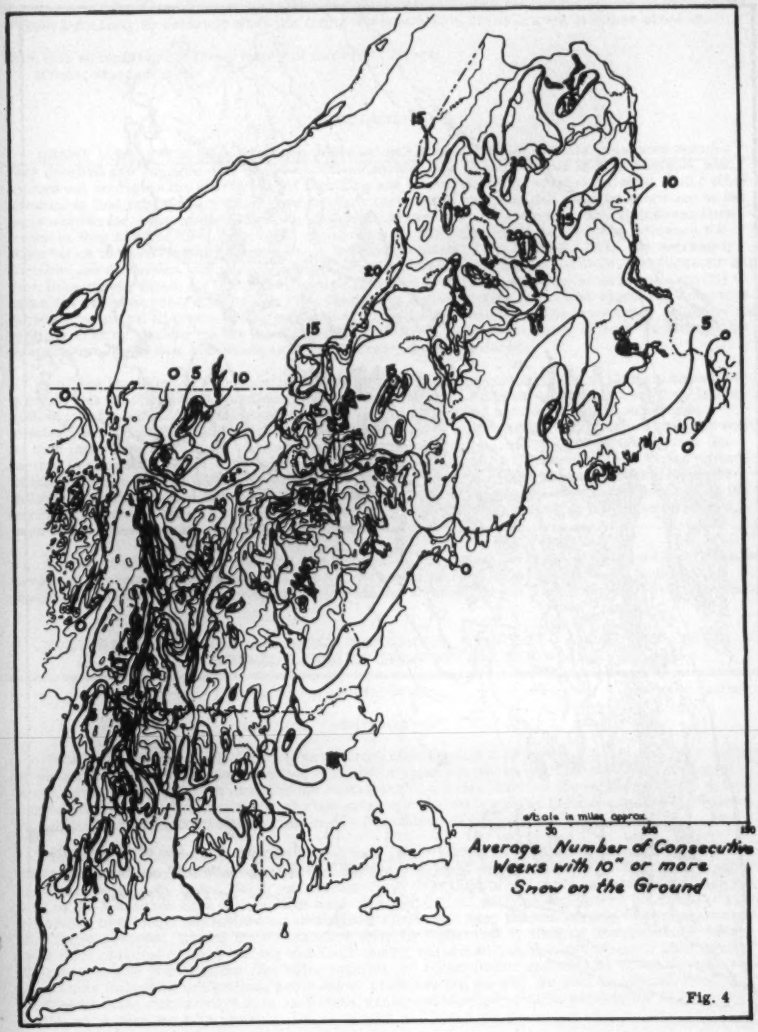

15
10
20
15
5
0 5 10
0
0
scale in miles approx.
30
60
120
Average Number of Consecutive
Weeks with 10" or more
Snow on the Ground

Fig. 4

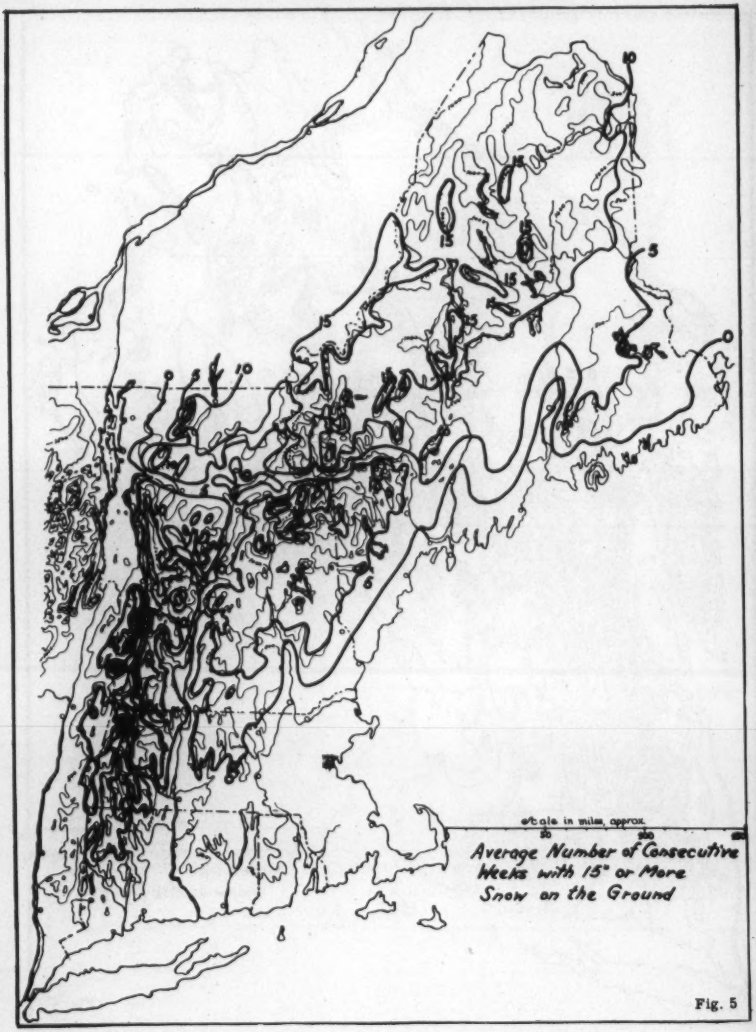

Average Number of Consecutive
Weeks with 15" or More
Snow on the Ground

Fig. 5

to suggest which of two distant or neighboring points probably has the longer season of snow-cover without indicating so certainly what the actual average length of the season at either place is.

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DISCUSSION

HENRY I. BALDWIN (now overseas, address not known)--Dr. STONE has presented some very detailed and valuable data on the depth and persistence of snow-cover in New England, and pointed out very ably the difficulties of obtaining and interpreting the source-material. Like other phenomena that vary greatly from year to year, snow-depth observations must be continued at the same station for many years before a significant average may be assured. Most depth-measurements in New England have been carried on only a decade. The many factors that influence the observation of snow-depths have been only briefly indicated by Dr. STONE. They are extremely variable and numerous. Of all meteorological data, probably the method of snow-measurement has been less standardized, or less consistently applied at exactly the same point and under exactly the same environment year after year. Thus changes in the vegetative cover and windbreaks due to the growth or removal of trees, or the erection or demolition of buildings and fences may influence not only the drifting of snow but the duration of a given depth. The consistency of snow as affected by temperature, rain, Sun, and shade is another factor to be considered.

Perhaps the effect of exposure cannot be illustrated adequately on maps of the scale used, but it is obvious that depth and duration of cover are greater on some exposures than others. During mid-winter the effect of drifting and sublimation resulting from northwest winds may cause a greater accumulation on south and southeast slopes. Late in the spring these slopes melt out sooner than those where the Sun's rays strike at an angle less normal to the surface, and where protection is afforded against warm southern winds. Areas at lower elevations lying to the northward of mountain ranges may also have their snow-cover preserved longer than a map with isopleths following contours would indicate. This results partly from the lower temperature induced by the surrounding snow-cover at higher elevations. Lacking sufficient observations, well-distributed, such small discrepancies cannot well be avoided.

The maps doubtless represent as detailed and as accurate a portrayal of snow-cover as can be prepared at present. There appears to be a very definite need for a standardized method for measuring the depth of snow lying on the ground and a much greater number of stations reporting.

SOME RECHARGE- AND DISCHARGE-PHENOMENA OF NORTH- AND SOUTH-FACING WATERSHED-LANDS IN THE WASATCH MOUNTAINS

A. R. Croft

Introduction

Within the Intermountain Region, water from melted snow that enters the soil and rock-mantle of mountainous drainage-basins during a period of about six weeks each spring is the principal supply that sustains stream-flow for the remainder of a year. Most of the major streams in this region flow westward or eastward, at right-angles to the main axis of the mountains and plateaus. Accordingly, a large portion of the water-yielding land faces toward the north or south.

South-facing slopes receive more solar energy per unit-area than north-facing slopes. These differences in energy have given rise to differences in local climates and, over the ages, to differences in relief, soil, fauna, flora, and stream-flow. The effects of aspect on detailed characteristics of the landscape have long been of interest to ecologists and physiographers but thus far inquiry regarding hydrologic phenomena on contrasting slopes has been limited largely to comparisons of discharge-records. During the stream-flow year 1943 (October 1, 1942, to September 30, 1943), data were obtained on north-facing and south-facing watershed-lands in the Wasatch Mountains of Utah concerning precipitation (including rainfall and accumulation and melting of snow), soil-water conditions (including infiltration, percolation, retention and losses), as well as stream-flow. A portion of these comparative data is herein presented together with an explanation of the conditions under which they were obtained.

Fig. 1--North-facing Miller Basin (upper) and south-facing Whipple Basin (lower), May 5, 1944

Study areas

The studies were made on areas within and adjacent to the Miller and Whipple Creek drainage-basins which are two of several tributaries of Farmington Creek that drains a portion of the west face of the Wasatch Mountains about midway between Salt Lake City and Ogden, Utah. The two study-basins have the common characteristics of being situated within the elevational zone of 6,500 to 8,500 feet and of having a highly fractured rock-mantle derived from granite, gneiss, and pegmatite, but are notably dissimilar in other respects.

Miller Creek, draining a basin of 252 acres, enters Farmington Creek from the south via a main channel about 1.1 miles long which has an average gradient of 18° and a mean direction of flow of north 10° east. Whipple Creek, draining a basin of 359 acres, enters Farmington Creek from the north at a point about opposite from Miller, via a channel 1.6 miles long which has an average gradient of 15° and a mean direction of flow of south 15° west (Fig. 1).

The north-facing Miller Basin slopes receive markedly less solar energy per unit-area and therefore dissipate less moisture in all seasons of the year than do the south-facing Whipple-Basin slopes (Fig. 2). By reason of these local climatic differences, the north-facing Miller-Basin slopes have a vegetal cover composed of dense patches of conifers, aspen, and tall brush with an understory of grasses and forbs, a litter-mantle that covers nearly all of the ground surface, and a soil-mantle that is high in organic matter. The south-facing Whipple-Basin slopes on the other hand have a vegetal cover composed chiefly of mountain brush, with an intermingling of sage-brush, grasses and forbs, a litter-mantle that is patchy and thin, and a soil that is low in humic material.

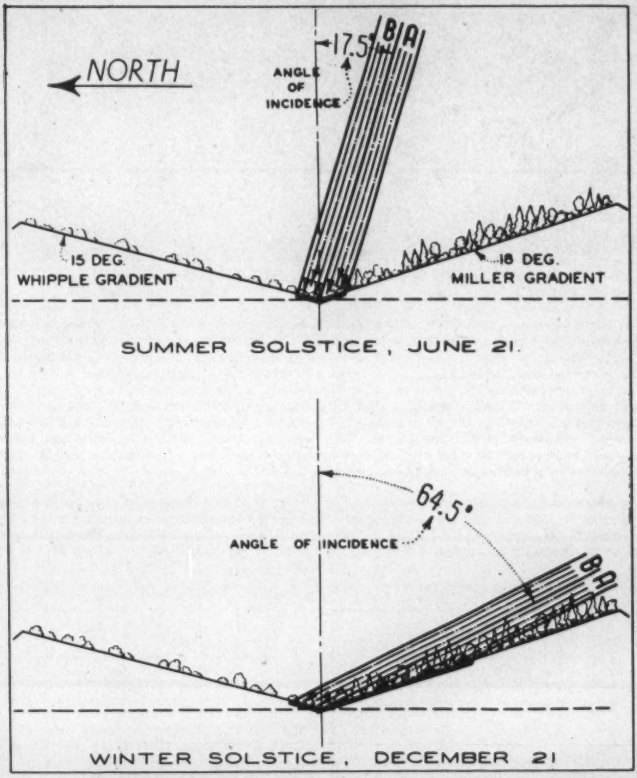

Fig. 2--Angles of incidence of Sun's rays at summer and winter solstices in relation to average gradient of north-facing Miller and south-facing Whipple basin-slopes [oblique rays (A) deliver less energy to Earth's surface per unit-area than less oblique, adjacent rays (B)]

Hydrologic data

Stream-flow from the Miller and Whipple basins was measured year-long using modified Venturi flumes and water-stage-recorders (Fig. 3).

Rainfall was measured during the late spring, summer, and early fall in four intensity-gages and 18 standard gages distributed over the two basins. During the winter months the extent of snow-coverage on each basin was mapped at weekly intervals.

Determinations of accumulation and melting of snow and of soil-water conditions were made on two sites, one being representative of the average conditions of insolation, soil, and vegetation prevailing on the north-facing Miller Basin and the other being representative of conditions on the south-facing Whipple Basin.

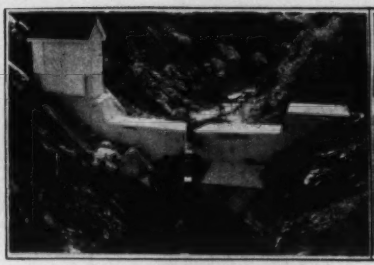

Fig. 3--Modified Venturi flume and broad-crested weir on Miller Creek

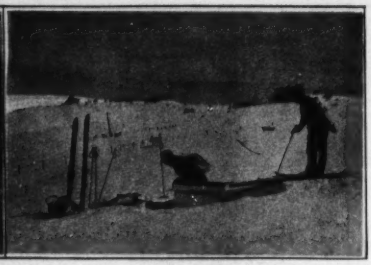

Fig. 4--Observer entering manway to soil-moisture sampling-pit

Snow-records were obtained on each site from three snow-storage gages and 15 snow-sampling stations at monthly intervals during the period October 1 to March 31 and at weekly intervals during April and May. The snow-storage gage records were assumed to represent the total snowfall. Amounts thus recorded were added to rainfall-records to obtain total monthly and year-long precipitation. The snow-cores obtained at the snow-sampling stations were assumed to represent the average accumulation of water in the snow-mantle. The difference between the amounts measured in the snow storage gages and the snow-cores was assumed to be the volume of water released from the snow by melting between measuring dates. Some of the water released from the snow no doubt was lost by evaporation, but it appears that most of it passed through the snow and entered the soil. No surface-runoff was observed during the snow-melting period.

Soil-moisture conditions were observed on each site at the same time snow-records were taken during the winter season and at more frequent intervals during the summer months by means of especially constructed concrete pits (Fig. 4). Two opposite walls of each pit were fitted with pipes that protruded horizontally 32 inches into the adjoining soil at depths of 3, 6, 9, 12, 18, 24, 36, 48,

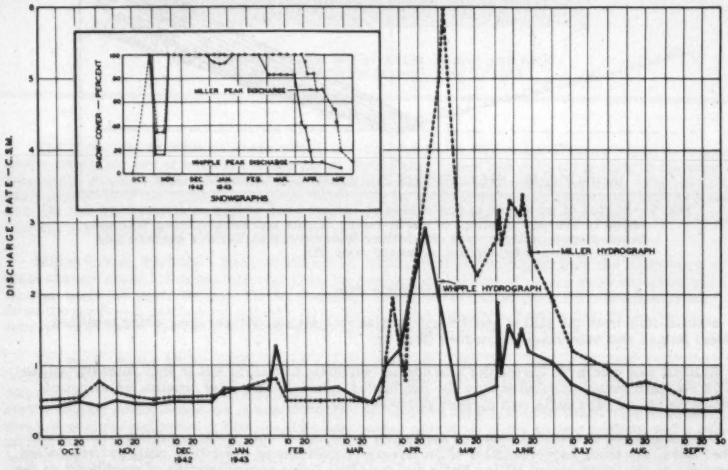

Fig. 5--Hydrographs and snowgraphs from north-facing Miller and south-facing Whipple basins

60, and 72 inches below the surface. Gravitational water was assumed to be in the soil if water dripped from the pipes when they were uncapped, or when water could be pressed with the fingers from samples of soil taken from beyond the end of the pipes. When free water was not present, soil-moisture determinations were made by weighing samples of soil taken from beyond the pipes before and after they were oven-dried. The soil-moisture content of samples taken immediately after gravitational water was observed to have moved below a given level was assumed to be a close approximation of the field moisture- or retention-capacity of that portion of the soil-profile. After weighting, in accordance with the depth of soil involved, the sum of the values thus obtained was taken to be the total retention-capacity of the six-foot mantle.

Stream-flow comparisons

Runoff from the two basins was much the same from October through March, the average discharge during this period being about 0.6 csm. During the remainder of the stream-flow year, however, discharge from the basins differed materially with respect to both timeliness and amount (Fig. 5). The south-facing Whipple Creek started to rise on March 25--five days earlier than the north-facing Miller Creek--and attained a maximum peak-flow on April 23--ten days earlier than Miller Creek. Peak-discharge from the north-facing Miller Basin was slightly more than twice that from the south-facing Whipple Basin. As is shown by the snow-graph insert in Figure 5, snow covered 70 per cent of the north-facing Miller Basin when that area produced its peak-discharge whereas when Whipple Creek attained its maximum discharge the south-facing basin had a snow-coverage of only ten per cent.

The per cent of the annual runoff from each basin by months was as in Table 1.

Table 1--Monthly runoffs

Months	North-facing Miller	South-facing Whipple
1942-43	pct	pct
October	3.8	5.1
November	4.6	5.4
December	3.8	5.6
January	4.7	7.7
February	3.6	7.3
March	3.6	6.9
April	17.5	19.4
May	22.2	10.5
June	18.6	14.5
July	8.4	8.4
August	5.3	4.9
September	3.9	4.3
Totals	100.0	100.0

It is worthy of note that during the winter period, October through March, when demand for water in the locality of these basins is low and where reservoir-construction is not feasible, the south-facing Whipple Basin yielded 14 per cent more of its annual runoff than did the north-facing Miller Basin. Conversely, the north-facing Miller Basin yielded 14 per cent more of its annual runoff than the south-facing Whipple Basin during the period April through June when there is a heavy demand for irrigation-water. In late summer, when irrigation-requirements are even more critical, both basins yielded about the same proportion of their total runoff. Thus, whereas both basins produced inadequate stream-flow in late summer, the north-facing Miller Basin is a more valuable watershed-area than the south-facing Whipple Basin because of the relatively greater volume of stream-flow it yields during the early summer months.

Precipitation-discharge relations

Total annual precipitation was essentially similar on both basins, the north-facing Miller Basin having received 33.14 inches and the south-facing Whipple Basin, 31.75 inches. As is shown by the mass-curves inserted in Figure 6, however, the north-facing Miller Basin yielded about 51 per cent of the annual precipitation as stream-flow whereas runoff from the south-facing Whipple Basin totaled 31 per cent.

Precipitation occurred in all months of the year, the least amounts per month occurring in July and September. Nearly two-thirds of the precipitation occurred as snow during the winter months and therefore did not reach the ground-surface until the snow melted (upper chart, Fig. 6).

Snow accumulated on both basins from November 1 to April 20 (comparative charts, Fig. 6). Snow-melting occurred over a period of 120 days (December 20 to April 20) on the south-facing Whipple Basin and over a period of 80 days (March 10 to May 30) on the north-facing Miller Basin.

Stream-flow in the north-facing Miller Basin began to increase on April 1, about 20 days after snow-melting began, and thereafter stream-flow discharge increased and decreased roughly in

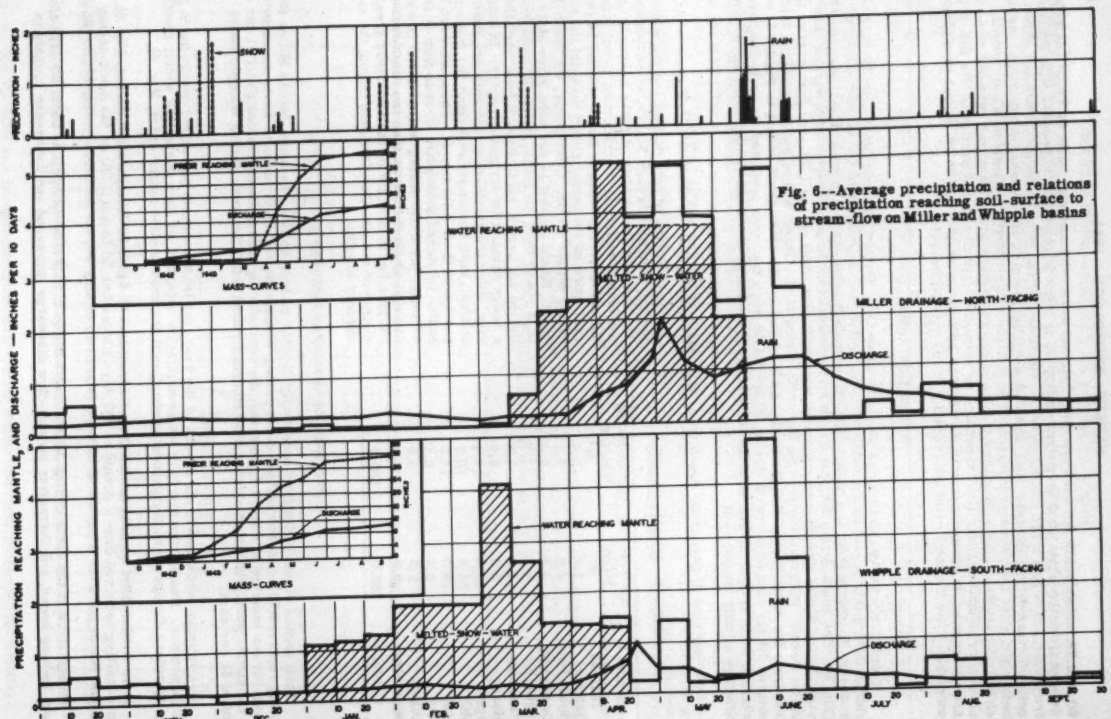

Fig. 6--Average precipitation and relations of precipitation reaching soil-surface to stream-flow on Miller and Whipple basins

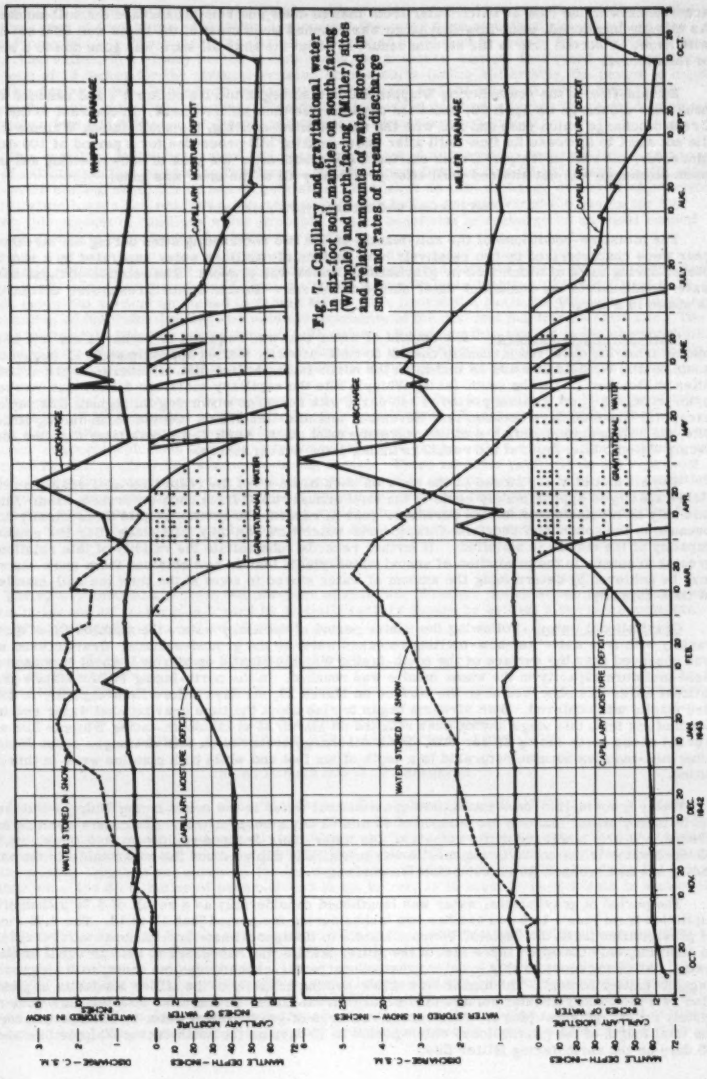

Fig. 7.--Capillary and gravitational water in six-foot soil-mantles on south-facing (Whipple) and north-facing (Miller) sites and related amounts of water stored in snow and rates of stream-discharge

accordance with the rate at which water from melted snow and rainfall reached the soil-surface. As already mentioned, peak-flow discharge was reached when most of the basin was still covered with snow. A second rise in the stream occurred about the time all snow was gone due to a series of rainstorms.

Stream-flow in the south-facing Whipple Basin also began to rise on April 1 and reached a peak-flow discharge on April 23, about ten days earlier than Miller Creek. In contrast to the Miller Creek discharge which rose and fell with the rate of snow-melting, the south-facing Whipple Creek did not start to increase its flow until after snow-melting had proceeded for a period of 100 days. Moreover, the rise in Whipple Creek started a full month after the peak of snow-melting and maximum discharge was not attained until after practically all of the snow was gone.

Soil-water and stream-flow relations

The moisture-conditions of the soil-mantle on the two contrasting sites during the stream-flow year were characterized by two relatively long periods of capillary water separated by a shorter period during most of which free or gravitational water was present. The relation of these soil-water conditions to the amount of water stored in the snow-mantle and to stream-flow discharge is shown in Figure 7.

Capillary-water recharge--The amount of water that was required to recharge six feet of soil-mantle from the observed minimum content to field-capacity totaled approximately 11 inches on the south-facing Whipple Site and 14 inches on the north-facing Miller Site. Recharge began at both sites on October 1. On the south-facing Whipple Site the capillary-moisture deficit was overcome prior to March 1, or within a period of 145 days, with recharge occurring throughout this period except for about 30 days between mid-November and mid-December. On the north-facing Miller Site, the soil-moisture deficit was not overcome until about April 1, a month later than the south-facing Whipple Site, most of the recharge taking place during March.

The amount of water stored in the snow on each basin when the respective soil-mantles reached field-capacity is approximately equal to the total annual runoff from each watershed-area. Although this may be a coincidence for the particular year of record, the relationship is theoretically sound because in the absence of overland-flow, ground-water flow can only take place after the retention-capacity of the mantle is satisfied. If further records substantiate the validity of this relationship, greater accuracy in the prediction of annual water-yields than is now obtained from snow-surveys may be achieved by determining the amount of water stored in snow at the time the soil-mantle is at field-capacity.

Gravitational water--Following the winter period of capillary water, the mantles filled quite rapidly with free water as snow-melting released water to the ground-surface. Gravitational water was observed near the surface of the south-facing Whipple Mantle on March 3, about five days after field-moisture capacity in the whole mantle was reached. In the north-facing Miller Mantle gravitational water was observed near the surface on March 23, six days before field-capacity in the entire mantle was achieved. Both streams began to rise about the time gravitational water reached a depth of six feet, this stage having been reached on March 23 at the south-facing Whipple Site and on April 4 at the north-facing Miller Site. Peak-discharge occurred on both drainages about 30 days after soil-mantles became saturated to a depth of six feet and while both mantles were in this condition.

Water from melted snow maintained gravitational water in the south-facing Whipple and the north-facing Miller mantles for periods of 45 and 65 days, respectively. After snow-melting had ceased, and only scattered drifts remained, the water-table dropped rapidly on both sites. By May 25, free water in the south-facing mantle was practically depleted and the water-table in the north-facing one had dropped three feet below the surface.

The period of gravitational water was lengthened considerably as a result of 4.75 inches of precipitation from June 1 to 5 and another two inches during the period June 13 to 16. The 4.75 inches of precipitation filled the depleted Whipple Mantle to its approximate gravitational water-capacity. In contrast, only the upper three feet of the Miller Mantle was necessary to hold an equal amount of water, indicating considerably greater gravitational water-capacity due, no doubt, to its higher soil organic-matter content. The higher free water-holding capacity of the Miller Mantle is suggested also by a materially greater volume of discharge from Miller Creek after both mantles were completely recharged about June 1. This second recharge of gravitational water by rainfall extended the total length of the gravitational water-period to 70 days on the south-facing Whipple Site and to 90 days on the north-facing Miller Site.

Capillary-water depletion--Depletion of capillary water occurred in two stages following the disappearance of free water. Depletion began about the same time on both sites--July 1. At the south-facing Whipple Site a moisture-deficit of 11 inches developed by August 20--a period of 50 days. Thereafter, in a 47-day period to October 9, the moisture-content decreased only one inch, or a total of 12 inches for the summer season. On the north-facing Miller Site, the period of rapid depletion during which 12 inches of water was lost extended to September 13, or 23 days longer than on the south-facing Whipple Site. This deficit increased gradually during the next 13 days until October 9 at which time a total seasonal deficit of 13 inches was attained.

After capillary moisture-content had apparently reached a minimum, recharge began as a result of rainstorms that started on October 9. Rainfall from October 9 to 29 increased mantle capillary-water content about 6.5 inches on both sites. Inasmuch as this recharge occurred after evapotranspiration losses had reached a low rate and shortly before snow covered the basins for the winter, this amount of capillary water probably was as beneficial in recharge as an equal amount of water stored in snow during the following spring.

Mantle retention-capacity--The rainstorms which occurred between June 1 and 5 shortly after gravitational water had disappeared from the south-facing Whipple Mantle and had dropped to 36 inches below the surface on the north-facing Miller Site, provided a basis for obtaining a rough approximation of the water-holding- or retention-capacity of the six-foot mantles on each site. The storms during this five-day period totaled 4.82 inches. By adding this amount to the observed maximum capillary-water contents of both sites indicates a total retention-capacity of about 16 inches on the south-facing Whipple Basin and of at least 19 inches on the north-facing Miller Basin.

Evapotranspiration loss--During the period July 1 to October 9, capillary moisture-depletion totaled about 12 inches on the south-facing basin-site and about 13 inches on the north-facing Miller Basin-Site, as heretofore mentioned. When summer rainfall of 1.4 inches is added to these amounts, evapotranspiration losses of approximately 13.4 inches and 14.4 inches, respectively, are indicated for the south-facing and north-facing basins. These amounts probably do not represent the total evapotranspiration losses for the year inasmuch as they do not include direct evaporation loss from the snow-mantle during the winter season or additional transpiration losses from vegetation having root-systems in permanent water-tables along the stream-channels. It is believed, however, that these amounts closely approach the actual losses on drained slopes.

Conclusion

The data presented are from but one year of records. Whether the relations indicated are essentially normal or materially biased by climatic factors should be evident after measurements have been continued over a period of years.

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REMARKS ON TURBULENT TRANSFER ACROSS PLANES OF ZERO MOMENTUM-EXCHANGE

F. A. Brooks and W. P. Berggren

Despite the advances in the statistical theory of turbulence, the PRANDTL [see 1 of "References" at end of paper] concept of mixing-length still affords the most convenient method of evaluating momentum-transfer from velocity-profiles in turbulent flow. In symmetrical conduits, eddy-diffusivity is known directly from the BOUSSINESQ quotient of shear-stress and velocity-gradient. Hence mixing-length is not essential for the expression of eddy-diffusivity in pipe-flow, but is convenient when the distribution of shear-stress is not known, as in most flow-problems in meteorology and hydrology.

PRANDTL noted the fault in his treatment calling for zero eddy-diffusivity at zero velocity-gradient [see equation (3a)], and he suggested that the velocity-gradient be taken as an average finite value throughout a neighborhood. Last year the authors [2] proposed an alteration of the PRANDTL equation which coincides with a literal interpretation of the phrase "average value throughout a neighborhood" as stated in GOLDSTEIN [3]. The correction proposed by PRANDTL [see equation (3b)] provides a smoother transition from the basic equation. PRANDTL'S correction does not seem to have come into use, possibly because he expected merely a small finite value of

eddy-diffusivity at pipe center (instead of zero). In contrast, a substantially uniform eddy-diffusivity was observed by WOERTZ [4], who found a linear change of vapor-pressure across the main central portion of a large flat duct (with steady evaporation from one wall).

In accord with the remark in GOLDSTEIN that "the turbulent interchange is not to be expected to vanish completely when (dU/dy) = 0", NIKURADSE [5] evaluated eddy-diffusivity nearly to zero at pipe center directly from known shear-stress and a smoothed curve of velocity-gradient. A very different result is obtainable by using a slightly different pattern for gradient-smoothing. NIKURADSE seems to have chosen a semi-cubic parabola for velocity-profile because this yields a reasonable curve for mixing-length, gradually approaching a maximum at pipe center. NIKURADSE [6], in a later paper, indicates the semi-cubic parabola as a method of fitting the central velocity-profile. With such a function, however desirable for mixing-length determination, it is mathematically necessary that eddy-diffusivity fall to zero at stream-center unless there is some special correction such as described above.

Reinterpretation of NIKURADSE'S observations of velocity-profile--Last year the authors called attention to the fact that NIKURADSE'S velocity-data might be fitted with equal validity by a curve slightly different from his choice. We are handicapped by his reporting velocities not as observed but as recalculated from a smoothed curve of graphically-determined velocity-gradients. It is our contention that, given a uniformly-distributed stream-line pressure-gradient and large-scale cross-flow fluctuations at the center, the proper fitting of an empirical velocity profile-curve to the almost equal velocities near the center should be such that the successive derivatives of the profile give smooth and logical curves across the line of maximum velocity. Figure 1 shows that NIKURADSE'S smoothed curve of (dU/dr) for a REYNOLDS number of 43,400 has a peculiar S-shape in a narrow central region (as needed to avoid a peaked mixing-length). The corresponding second derivative would suddenly jump to large magnitude at pipe center. A good fitting of the central velocity-profile

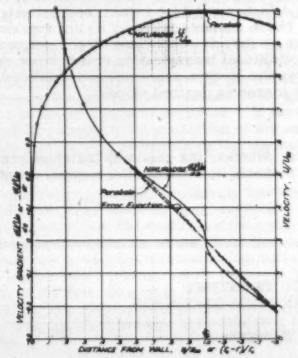

Fig. 1--Velocity and velocity-gradient distribution across a pipe as reported by Nikuradse and as reinterpreted to avoid low eddy-diffusion at center

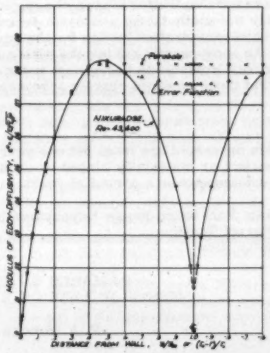

Fig. 2--Variation of eddy-diffusivity across a pipe as reported by Nikuradse and as reinterpreted

can be made with a parabola of degree 1.75, but this leads to a similar S-variation in (dU/dr) at pipe center (though of less magnitude).

A regular parabola of the second degree, however, as used by SHERWOOD and WOERTZ, yields desirable linear variation through the stream-center for velocity-gradient, and a constant second derivative. This is shown in Figure 1. The corresponding eddy-diffusivity, constant across the central half of the pipe, is shown in Figure 2 by symbol x. This parabola fits the velocity-profile reported by NIKURADSE for Re = 43,400, within 0.6 per cent at the center-line, but will not yield finite mixing-length at the center unless equation (2a) is modified.

A closer fit to the reported profile can be made by using an error curve $U = (A + Be^{-cr^2})$, where r is distance from center-line. The corresponding eddy-diffusivity, which decreases at the center to 93 per cent of maximum, is shown in Figure 2 by symbol Δ. This shape is more in accord with the reduced turbulence velocity-components reported by KALINSKE [7] when interpreted by $\epsilon = \ell\sqrt{w^2}$. For example, from KALINSKE'S Figure 7 the ratio of $\sqrt{w^2}$ for center versus $(z/z_m) = 0.5$ is approximately 0.7. This, combined with a corresponding mixing-length ratio of 1.22, gives a ratio of 0.85 for eddy-diffusivity at center compared to maximum [at $(z/z_m) = 0.5$].

Such slight revisions of velocity-profile, by either second-degree parabola or the error-curve, avoid the untenable central dip to near zero for eddy-diffusivity reported by NIKURADSE. SHERWOOD and WOERTZ, taking "eddy-viscosity" ("eddy-viscosity, ϵ" of SHERWOOD and WOERTZ corresponds to Austausch-coefficient $\rho\epsilon$ of this paper) constant across the major central portion of a duct, show that over a considerable range of REYNOLDS number the eddy-diffusivity for vapor-transport is about 1.6 times that for momentum-transfer [equation (1)].

The acceptance of either of these slightly different representations of NIKURADSE'S velocity-profile, although satisfying the basic eddy-diffusivity problem, leads to serious difficulties if one continues to use the original PRANDTL mixing-length equation (2a) for shear-stress. At zero-gradient the mixing length would still need to be infinite to yield a finite eddy-diffusivity at pipe center [see equation (3a)]. For symmetrical conduits a separate treatment directly of eddy-diffusivity would be more useful. SHERWOOD and WOERTZ in their equation (26) suggest that the eddy-diffusivity for the central region of a conduit can be estimated from mean velocity, friction-factor, and distance from wall to stream-center. It is significant that their value of "eddy-viscosity" for air at Re = 43,000 coincides with the maximum value we find for water from NIKURADSE'S data, where both are expressed in dimensionless form, $\epsilon^* = (\epsilon/r_o\sqrt{\tau_o/\rho})$.

Extension of eddy-transfer characteristics of conduit-flow to single-surface flow-systems--For outdoor problems of stream-flow and of heat- or mass-transfer, there is needed some reliable method of estimating eddy-diffusivity simply from surface-condition, the observed velocity-profile, and characteristic turbulence. In density-currents there are planes of zero shear-stress with the velocity-profile above this level not symmetrical with that below. There are usually also one or more planes of inflection of velocity-profile which again do not stop heat- or moisture-transfer, if as usual there exist finite temperature- or humidity-gradients across them. The desired expression for eddy-diffusivity, therefore, can depend exclusively neither on velocity-gradient (which goes to zero at the plane of maximum velocity), nor on the second derivative of velocity (which goes to zero at inflection-points on the profile).

In order to avoid the zero-gradient dilemma, the authors advocated last year a dual calculation straddling the plane of zero shear-stress, based simply on the fact that the size of the turbulence-eddies is not a mathematical infinitesimal, but is comparable with the distance from a surface; and consequently that effects of opposite shearing can be felt to a considerable distance across stream-center. Thus we say that at pipe center there is zero shear-stress not because of the absence of cross-flow, but because there is here a balanced exchange of considerable momentum. This view is analogous to the established concept that evaporation is the net result of simultaneous rates of condensation and of vaporization.

The most obvious evidence of the distance (from the center-line of maximum velocity) to which some effect from the opposite side of the stream can be felt is seen in the typical velocity-profile near stream-center, where it falls below that indicated from friction-effects of the nearest wall. PRANDTL and TIETJENS [8] show this vividly in their Figure 42. For fluid flowing past a single surface, there should be a continuous rate of increase of average velocity depending upon similarity of flow-pattern. Such a profile would extend indefinitely, were it not limited by an opposing profile. The velocity-gradient at this junction would appear discontinuous if the shear-resistance turbulence-eddies were of infinitesimal size. Hence the extent of central rounding is an indicator of the cross-stream distance of effective turbulent transport, which transport is related to eddy-diffusivity.

NIKURADSE'S [5] Figure 20 for moderate REYNOLDS numbers confirms the 1/7-power law deduced by PRANDTL from the BLASIUS law for pipe flow-resistance (inversely proportional to the fourth root of REYNOLDS number). For increased REYNOLDS numbers, NIKURADSE found the expenent to decrease to 1/10, which again is in accord with pipe flow-resistance found at high REYNOLDS number. The distance from the wall to the point of departure from the above power-law representation varies in NIKURADSE'S seven examples from $0.7r_o$ for low REYNOLDS number to $0.8r_o$ for high REYNOLDS number. The corresponding distances from the center are two (or less) times the NIKURADSE mixing-length for the central regions. (See Table 1 for designations of symbols.)

Table 1--List of symbols

Symbols	Definition
A, B, c	Constants in error-curve velocity-profile expression
e (= 2.718+)	Base of natural logarithms
ℓ [ft]	Prandtl mixing-length
ℓ_c [ft]	Corrected mixing-length for uniform eddy-diffusivity
ℓ_1 [ft]	Auxiliary mixing-length in Prandtl correction-term
Re	Reynolds number (dimensionless modulus)
r [ft]	Distance from center to any point in stream
r_o [ft]	Radius of pipe
U [ft/sec]	Mean velocity at any location
U_m [ft/sec]	Mean velocity at plane of zero shear-stress
u [ft/sec]	Fluctuating component of velocity in direction of stream
w [ft/sec]	Fluctuating cross-stream velocity
z [ft]	Distance from zero-velocity plane
z_m [ft]	Distance from plane of zero-velocity to plane of zero shear-stress
ϵ [ft^2/sec]	Eddy-diffusivity
ϵ^* ($= \epsilon/[r_o\sqrt{\tau_o/\rho}]$)	Dimensionless modulus of eddy-diffusivity
ρ [lb sec^2/ft^4]	Mass-density of fluid
τ [lb/ft^2]	Shear-stress at any plane
τ_o [lb/ft^2]	Shear-stress at plane of zero-velocity

Further distinct evidence of distance of cross-stream effect is seen in the WATTENDORF [9] curve for correlation of velocity-components. This shows a constant value from near the wall to about 0.6 (z/z_m). (The correlation-coefficient must go through zero at channel-center in passing to opposite sign.) VON KARMAN [9] states that the flow-pattern must be "similar" over the region of constant correlation. Thus it seems proper to consider the point of falling off of the coefficient near the stream-center as another indication of the extent of cross-stream influence of dissimilar flow-pattern. In this example the distance is more than twice the NIKURADSE mixing-length indicated for the central region.

These two evidences of relatively extended cross-stream influence do not explicitly indicate the actual mean mixing-length, nor eddy-diffusivity, because the reduction of velocity at the center-line (by opposite shear) itself affects the single-side velocity-profile (influenced by deficient momentum arriving from the slowed central region).

Now in reviewing the whole problem it is recognized that the excessive curvature that indicates the extent of cross-stream influence of dissimilar flow-pattern is of itself a measure of the degree of this retarding influence. The degree of curvature is indicated approximately by the second derivative of the velocity-profile. Thus we are led to PRANDTL'S form of correction (in which he included both first and second derivatives), now extending it across most of the flow-section. Although eddy-diffusivity is the flow-characteristic for turbulence-exchange, its evaluation near a surface is not possible from velocity-profile alone. The parameters in the alternate PRANDTL expression (3b) can still be thought of as mixing-lengths. It is probable that such mixing-lengths will be more nearly invariant under outdoor conditions than eddy-diffusivity.

Analysis of PRANDTL'S mixing-length concept for constant eddy-diffusivity across the plane of zero shear-stress--The basic equation for shear-stress of BOUSSINESQ, defining eddy diffusivity (ϵ) is

$$\tau = \rho\epsilon(dU/dz) \qquad (1)$$

where $\rho\epsilon$ is known as the Austausch-coefficient. The PRANDTL equation for shear-stress is

$$\tau = -\rho\overline{uw} = \rho\ell^2\left|dU/dz\right|(dU/dz) \qquad (2a)$$

which (for one side of a pipe or channel) is a simple interpretation of the REYNOLDS stress by axial and cross-flow fluctuations combined by an unstated correlation-coefficient. As mentioned previously, this expression is faulty at (dU/dz) = 0.

As a result of these two equations, the expression for eddy-diffusivity, used by NIKURADSE in determining mixing-length, is

$$\epsilon = \ell^2 \left| dU/dz \right| \tag{3a}$$

This expression is untenable at (dU/dz) = 0 for transport of entities subject to a potential-gradient not zero at the plane of zero shear-stress.

To overcome this defect, PRANDTL [10] suggested that one consider

$$\epsilon = \ell^2 \left[(dU/dz)^2 + \ell_1^2 (d^2U/dz^2)^2 \right]^{1/2} \tag{3b}$$

applied near the center. This expression replaces the simple gradient of equation (3a) by a vector-resultant including as a normal component the curvature of velocity-profile (reduced to proper dimensions by an auxiliary mixing-length). If the velocity-profile approaching the center of a pipe or channel can be well represented by a curve whose second derivative is constant or rises to a finite maximum (or if mixing-length increases toward the center), the magnitude of eddy-diffusivity can increase in spite of the first term going to zero at the center-line. Thus, this two-term expression can give the desired sustained value of eddy-diffusivity across the plane of zero shear-stress, if appropriate functions are found for the mixing-lengths.

If the modified expression (3b) is used [retaining equation (1) defining eddy-diffusivity] the original PRANDTL expression (2a) will be altered to

$$\tau = \rho \ell^2 \left[(dU/dz)^2 + \ell_1^2 (d^2U/dz^2)^2 \right]^{1/2} (dU/dz) \tag{2b}$$

Evaluation of corrected mixing-length--Assuming that the velocity-profile across the main central region of a pipe can be well fitted by a regular parabola, the second derivative is constant and when multiplied by ℓ_1 (regarded as a distance from center-line) equals the value of the velocity-gradient (dU/dz), at that distance. Thus, if one desires the brace of equation (2b) to have a center value leading to an eddy-diffusivity equal to NIKURADSE'S peak-value [found at $(z/z_m) = 0.5$], one may take $\ell_1 = 0.5\ z_m$ (constant), which will make the second term uniformly equal the value taken by the first term at $(z/z_m) = 0.5$. Then with a corrected mixing-length ℓ_c (equal at the center to the NIKURADSE ℓ at 0.5) one obtains the desired high central value for eddy-diffusivity. The new shoulder value can be retained equal to the old maximum by appropriate reduction of the corrected mixing-length in this region.

In Table 2, values of the dimensionless modulus of eddy-diffusivity, $\epsilon^* = (\epsilon / r_0 \sqrt{\tau_0/\rho})$, are given corresponding to the 1/7-power law up to $(z/z_m) = 0.462$, and to a parabolic profile from this location to the plane of maximum velocity. These computations, giving constant eddy-diffusivity over the parabolic range [based on equation (1) with linear shear-stress variation], are represented by the symbol x in Figure 2 for comparison with the NIKURADSE eddy-diffusivity for Re=43,400.

Column (b) of Table 2 gives the values of ℓ_c required to fit the uniform variation of ϵ^*[column (a)] across midstream when the PRANDTL correction is used with $\ell_1 = 0.5\ z_m$. Column (c) shows the fairly close fit to these values provided by the function

$$(\ell_c/z_m) = 0.117 \tanh 2.6\,(z/z_m)^{1.16} \tag{4}$$

It should be noted, however, that values of ℓ_c computed from equation (4), when substituted into equation (3b), will not identically reproduce the desired variation of ϵ^* [defined by Column (a) of Table 2]. The ϵ^*-values computed by equation (3b) will show local irregularity near the location $(z/z_m) = 0.462$, because of the junction of two profile-functions (even though the velocity and its first and second derivatives were matched at this point in joining the parabola to the 1/7-power curve). The small departures of the empirical function (4) from the required values of (ℓ_c/z_m) in Column (b) are intensified by the squaring operation in equation (3b).

Recalling that the mixing-length values of Column (b) are specific for the composite profile-representation mentioned above, it is felt that the expression (4) should be more generally applicable for incorporation with smoothed observations of velocity, velocity-gradient, and second derivative in the extended application of the PRANDTL correction (3b) for prediction of eddy-diffusivity in atmospheric or hydrologic systems.

Table 2--Corrected mixing length for uniform eddy-diffusivity

Fractional dist. surface to plane, max. vel., (z/z_m)	(a) $\epsilon^* = \epsilon/\tau_o\sqrt{\tau_o/\rho}$	(b) (ℓ_c/z_m)	(c) $0.117 \tanh 2.6\,(z/z_m)^{1.16}$
0.00	.00000	.000000	.000000
0.01	.00567	.000870	.001456
0.02	.00995	.002195	.003260
0.04	.01805	.005640	.00725
0.07	.02910	.01211	.01387
0.10	.03710	.01865	.02081
0.15	.04962	.03090	.03278
0.20	.05977	.04346	.04473
0.30	.07400	.06692	.06632
0.40	.08124	.08653	.08360
0.462	.08236	.09612	.0920
0.50	.08236	.09793	.0962
0.60	.08236	.10285	.1045
0.70	.08236	.10795	.1097
0.80	.08236	.1122	.1129
0.90	.08236	.1153	.1146
0.96	.08236	.1163	.1154
0.98	.08236	.1164	.1155
1.00	.08236	.1165	.1157

Conclusion--It has been noted that the velocity-profiles reported by NIKURADSE are not direct observations but are based on smoothed gradients. The pattern of smoothing gives reasonable mixing-lengths, but calls for zero eddy-diffusivity at pipe center, contrary to findings by WOERTZ. A slightly different interpretation of NIKURADSE'S reported profile, with a greatly extended application of the correction PRANDTL suggested at zero-gradient, leads to uniform eddy-diffusivity across the main central portion of the pipe. The corrected mixing-length to suit this interpretation is similar to NIKURADSE'S, but of reduced magnitude. It is hoped that this revised treatment will permit calculation of heat- and moisture-transport from the ground under usual atmospheric conditions.

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DISCUSSION

A. A. KALINSKE (State University of Iowa, Iowa City, Iowa)--The authors discuss and analyze a problem relating to exchange-phenomenon in turbulent flow which has bothered everyone who has had occasion to calculate eddy-diffusion coefficients, whether for closed or open conduit water-flow or in the atmosphere. They point out very effectively that the turbulent exchange-coefficient is not necessarily zero when the velocity-gradient is zero. Thus at the center of a pipe the eddy-diffusivity cannot be evaluated since the net rate of exchange of momentum is zero giving a zero shear-stress. In fact the calculation of the eddy-diffusivity even near the point of zero velocity-gradient is not very satisfactory due to the difficulty in obtaining an accurate value of the velocity-gradient. Thus, in many practical problems, it becomes difficult to calculate the eddy-diffusivity for a large region of the flow-section.

Of course, when the shear-stress is not known, as occurs in many atmospheric problems, the eddy-diffusivity then must be calculated from the velocity-distribution data alone. This is the problem the authors discuss, and for which they develop relations between the eddy-diffusivity, mixing-length, and velocity-gradient. They develop a relation for the so-called mixing-length which gives values for eddy-diffusivity which are practically constant across the midsection of a pipe; and they suggest that this mixing-length relation can be used for calculating the eddy-diffusion coefficient for other flow-problems. Whether their relation will give proper values for eddy-diffusivity for various meteorological and hydrological problems is somewhat doubtful. In any case, calculated values ought to be checked against directly measured values of ϵ.

It should be pointed out that PRANDTL never intended that the relation [equation (2a)] between shear, ℓ, and (du/dy) apply to any conditions other than near a boundary, and therefore extending its use to the center of the pipe is not warranted. Various data on the value of ϵ, as obtained by direct methods, for flow in pipes or in rectangular conduits seems to indicate that ϵ always decreases towards the center; however, not to as low a value as shown by NIKURADSE in the authors' Figure 2. For water-flow in wide open channels, the maximum value of ϵ is at mid-depth, while the maximum value of a length factor associated with the diffusion-process occurs at a point somewhat above mid-depth. The writer has made extensive measurements of ϵ-values for open-channel water-flow by measurements of the diffusion of foreign matter. Some of these data are reported in the following two papers: "Experiments on eddy-diffusion and suspended-material transportation in open channels" [Trans. Amer. Geophys. Union, Part II, pp. 530-535, 1943] and "Eddy-diffusion" [Ind. and Eng. Chem., v. 36, p. 220, 1944].

The writer believes that the authors' analysis relating to mixing length is most worthwhile since it is one approach to the evaluation of the eddy-diffusivity. However, the writer feels that the direct measurement of ϵ by diffusion-measurements should give much more accurate values and is probably the only method that is reliable for other than the simplest boundary-conditions. The technique for measuring ϵ by diffusion-experiments as described in the previously mentioned papers is not particularly involved and can no doubt be simplified so that the work would not be greatly in excess of that for obtaining accurate velocity-data. In other words, the writer's contention is that if ϵ cannot be obtained accurately using momentum-transfer phenomena, then measurements on the transfer of other quantities can be made and ϵ can thus be obtained more directly.

F. A. BROOKS and W. P. BERGGREN (authors' closure to discussion)--The authors are appreciative of Dr. KALINSKE'S comments and look forward to further data from him and others which will permit direct comparison of eddy-diffusivity determined from the atmosphere and open-channel water-flow with that for pipe- or conduit-flow in which the shear-stress and velocity-distributions are known.

As to the general applicability of our revised mixing-length equation (4), we wish to explain that this is a best-fitting for a corrected PRANDTL formula extended to suit both the NIKURADSE pipe-flow data and the SHERWOOD and WOERTZ vapor-transport observations. The PRANDTL correction used was specifically designed by PRANDTL for the pipe center. It should be stated that expression (4) is not a desirable mathematical form at the wall ($z = 0$) because of zero-slope for an exponent greater than unity on the argument of the hyperbolic tangent. [A straight line from the origin would be tangent to this curve at $(z/z_m) = 0.24$.]

PRANDTL [11] has recently offered another expression for eddy-diffusivity in the central region of a jet which may be useful for general stream-transport analyses. This replaces mixing-length with a breadth, b, of mixing-zone, and substitutes a velocity-difference in place of velocity-gradient.

$$\epsilon = Kb\,(U_{max} - U_{min}) \qquad (5)$$

It is seen that this avoids the difficulty at zero velocity-gradient in a different manner from his original correction [our equation No. (3b)]. GÖRTLER'S [12] calculation of jet velocity-profiles by this new equation shows a broader central peak conforming better to REICHARDT'S observations than the TOLLMIEN solution which used the original equation [No. (2a)]. If the same procedure were applied to pipe-flow profiles the new calculation should be more like our reinterpretation of the NIKURADSE data. The recent expression (5) can be reduced to a form nearly identical to that proposed by the authors in 1943 [2, pp. 195-196 and Fig. 2]. Possibly the use of data from a pair of points, as required by these treatments, will be found preferable to using the second derivative [equation (3b)].

The authors do not agree that PRANDTL restricted his original mixing-length equation [equation (2a)] to the neighborhood of a boundary. Our interpretation that he expected it to apply near (but not at) the pipe center is based on his original paper [10] in which he specifically recommended a correction [equation (8b)] "at pipe center". This is confirmed by the use of the uncorrected equation at $(r/r_0) = 0.02$ by PRANDTL'S coworker NIKURADSE [5].

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COMPACTION IN CULTIVATED SOILS

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Introduction--Many soils which in their native state were mellow, of low apparent density, and highly permeable to water, have become compact and highly impermeable under cultivation. Other soils, although cultivated as often, still remain fairly permeable. Soils men have long advocated the necessity of reducing the amount of cultivation, and the desirability of selecting a time for field-operations when the moisture-content of the soil is such that the bearing power of the soil is adequate to safely carry the equipment. The importance of soil-particle size in relation to compaction has not been stressed. Observations in citrus orchards in southern California indicated that cultivation produced the highest densities and the greatest reduction in water-penetration on those soils in which there was a wide range of particle-sizes, such as the gravelly loams derived from igneous rocks high in quartz. This idea is in agreement with the FULLER curve concept used in designing concrete mixes, and in the construction of earth fill dams [see 3 of "References" at end of paper].

Early in 1937 the Agricultural Extension Service asked for a study of the cause of poor water-penetration in an old citrus orchard planted on a Hanford gravelly-loam soil (a soil derived from acid igneous rock). The orchard had been irrigated with sewage-effluent and often cultivated when the soil-moisture was high. Base-exchange studies on the soil made by Dr. APPLEMAN showed that calcium and magnesium composed about 45 per cent of the bases in the upper foot, and slightly more than that in the lower depths. Information on the soil-conditions found in this orchard is presented in Table 1. The weight per cubic foot of dry soil, the number of strokes with a ten-pound hammer dropped a unit-distance required to drive a soil-tube six inches, and the moisture-content of the soil at time of sampling are recorded. This is a recent alluvial soil without natural horizons. The compacted soil in the zones zero to six inches and six to 12 inches below the bottom of the mulch are the results of cultural operations, mainly cultivation. If we assume 81 pounds as the dry weight of a cubic foot of this soil under natural conditions, the pore space in the six-inch to 12-inch zone would have been reduced about one fourth through compaction. Permeability of the soil is not only reduced by the total reduction in pore-space but also by the reduction in pore-size.

In recent years a goodly number of orchard soils have been examined for soil-compaction. The greatest compaction found was in an orchard located on gravelly-loam soil on a recent alluvial fan. The conditions observed are indicated in Figure 1. This orchard had been heavily cultivated with a disc-harrow, possibly at times when the moisture-content of the soil was high. The compacted soil had an apparent density about 50 per cent higher than in its natural state. No roots were found in the highly compacted soil. Soil-particle sizes ranged from gravel that would be retained on a

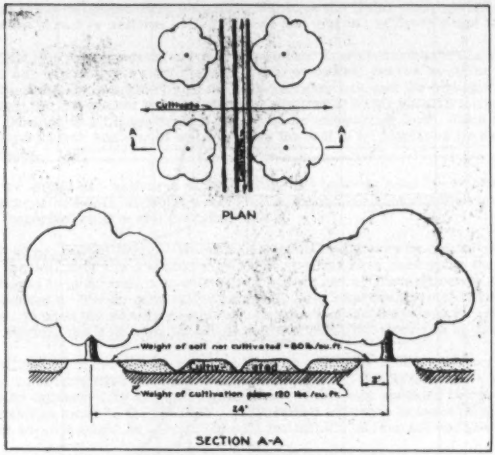

Fig. 1--Outline of soil-compaction in an orange grove on gravelly loam-soil

Table 1--Measurements of soil-compaction in Crown City Orchard, Pasadena

Soil-depth	Weight dry soil per ft[3]	Impact No.[a]	Moisture
in	lb		pct
Mulch	...	...	8.2
0-6	96	32	7.6
6-12	101	31	7.4
12-18	90	14	7.4
18-24	90	11	7.7
24-30	84	9	7.4
30-36	81	5	9.2

[1] [a]Number of strokes with a 10-pound hammer required to drive a soil-tube 6 inches.

one-inch mesh sieve to highly colloidal particles. Mechanical analyses made with TYLER standard screens gave the following average values, expressed as percent, for the soil retained on each screen: No. 2, 12.3; No. 4, 8.4; No. 8, 7.2; No. 14, 8.4; No. 28, 10.4; No. 48, 9.3; No. 100, 15.2; No. 200, 7.9; greater than 200, 20.3.

Laboratory compaction-tests--Using facilities made available by the Metropolitan Water District of Southern California, compaction-tests were made on soil-samples at various moisture-contents. The method used was the same as that employed by the United States Bureau of Reclamation for materials to be used in earth-fill dams. The compaction obtained is similar to that produced by the implement known as the sheepsfoot-roller which is used in dam-construction.

Partial mechanical analysis, moisture-equivalent values, maximum density, and percolation-rates are given in Table 2. Low percolation-rates are associated with the soils of high density.

Curves indicating relationship between moisture-percentage and dry weight of compacted soil, and moisture-percentage and resistance offered to a PROCTOR [2] needle are shown in Figure 2. The Hanford, Delhi, and Ramona soils are Nos. 2, 3, and 5 of Table 2. The moisture-equivalent values, indicated by ME on the graphs, are about equal to the field-capacity for the Ramona and Hanford soils, but about half the field-capacity in the case of the Delhi sand. Field-capacity is a term used to indicate the relative amount of moisture a well-drained soil will hold against gravity. The soil classed as Ramona sandy loam has a well-proportioned wide distribution of particle-sizes. It can be compacted to a high density, a weight of 134 pounds per cubic foot having been attained at a moisture-content of eight per cent. The Hanford sandy loam was not as well proportioned as the

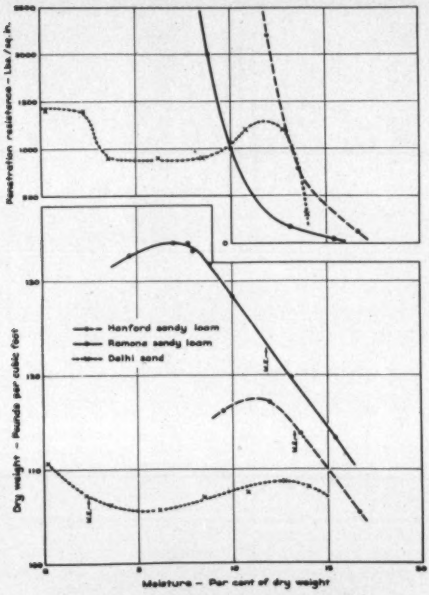
Penetration resistance - Lbs./sq. in.
Hanford sandy loam
Ramona sandy loam
Delhi sand
Dry weight - Pounds per cubic foot
Moisture - Per cent of dry weight

Fig. 2--Relationship between soil-moisture and resistance to rod forced into the soil, and soil-moisture and apparent density, for three soil-types

Table 2--Characteristics of soils used in compaction-studies

Soil[a]	Mechanical analysis of soil retained on sieve[b]			Moisture equivalent	Max. density, dry soil	Moisture at max. density	Percolation-tests[c]	
	4	8	14				Head	Rate
					lb/ft^3	pct	in	cc/hr
1	1.4	3.0	6.0	11.6	118	12	140	3
2	1.4	2.0	5.3	13.3	117	12	140	4
3	0.0	0.0	0.5	2.3	111	0.2	28	60
4	1.6	2.4	5.5	14.0	126	9	140	2
5	4.1	10.0	15.2	11.8	134	8	140	1
6	0.0	0.0	0.1	9.8	113	13	140	10
7	0.3	1.5	5.0	12.4	126	9	140	2

[a]Soil: 1 and 2 = Hanford sand-loam; 3 = Delhi sand; 4 = Placentia sandy loam; 5 = Ramona sandy loam; 6 = loamy sand; 7 = Hesperia sandy loam. [b]Sieve-mesh, in inches: 4, 0.185; 8, 0.093; 14, 0.046. [c]Percolation-rate in cc/hr through a soil-core 4 inches in diameter and 2 inches in thickness consolidated under a load of 1000 pounds per square foot.

Ramona soil so lower densities were obtained. Tests on the Delhi sand, a wind-blown soil with rounded particles of rather uniform soil, produced two maxima of density and bearing-power.

HOGENTOGLER [1] has pointed out that if moisture is expressed as a percentage of the volume rather than as per cent of dry weight the weight-water-content curves would be a series of straight lines. Until the demands of hydration of the soil-particles are met the addition of water does not materially affect the compacted weight. Further addition of water acts as a lubricant which permits the particles to adjust to a higher density for the same compacting load. Once the maximum density has been reached further addition of water causes the soil to be displaced by water thus resulting in lower densities.

Because the weight per unit-area of most of the implements used in cultivating are not extremely high, vibration of the soil, especially when the soil contains enough water to act as a lubricant, must play an important rôle in soil compaction.

Reduction of compacted layers--Breaking of compacted layers by means of sub-soilers or chisels when the soil is dry is a common practice. Claims have been made that compacted layers have been reduced by practicing non-cultivation culture and by the application of organic matter and soil-amendments. Water-penetration generally does improve when cultivation is restricted. This, however, is often the result of improved structure of the surface-soil. Poor structure often results from working the soil when so wet as to form clods, or so dry as to produce a dust surface.

WINTERKORN [4] observed the slacking-time on a number of dry cohesive subsoils when treated with solutions containing specific ions. While slacking time was associated with rate of wetting, this in turn was also influenced by the specific ion used. Generally speaking the sodium solution took the longest, the calcium close to the shortest. If gypsum is effective in increasing the permeability of the compacted layer it might be associated with the affinity of internal soil-surface for water.

Summary--In many orchards in southern California the penetration of rain and irrigation-water into the soil has been restricted by a compacted layer produced by cultural operations. Investigations have shown that this trouble is dominant on alluvial soils derived from igneous rocks high in quartz. These soils often have a good distribution in particle-size from coarse gravel to clay. Reductions in pore-space as great as 50 per cent have been observed in the field.

The degree of compaction under uniform loading and variable moisture-content has been determined on a range of soils. Curves representing relationships between moisture-percentage and soil-density, and moisture-percentage and resistance to a PROCTOR needle are shown for three soils. Soils with wide ranges in particle size were compacted to a much higher density than uniform grain size soils.

The effect of vibration on compaction and methods of improving water penetration on compacted soils are discussed.

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A NEW METHOD OF SEDIMENT-TRANSPORTATION

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The writer has observed in two streams a method of transportation of solids in suspension which he has not seen described in any literature, and which may therefore present a method of the transportation of sediment which is new to this science.

The observations were made in the Canadian River near Tulsa, Oklahoma, and in the Root River in southeastern Minnesota. In both of these streams the water was flowing on a bed of clean sand and was clear, so that the phenomena could be observed. The sand-bed was in the form of ripples, which consisted of a series of small bars scattered irregularly over the bed of the stream with relatively flat upstream slope and steep downstream slope. In the Canadian River the action occurred over a large area of the stream-bed, but in the Root River it acted only at a single point. The phenomena consisted of an upward-moving turbulent current which started from a point on the downstream-sloping face of the ripple and carried the bed-material upward. This turbulent current extended to the surface, where it spread out and mixed with the horizontal current of the stream and the sediment carried up with it spread out with the current and gradually settled back to the bottom. These upward currents did not move from place to place, but remained stationary, always rising from the end of the same ripple. It has been suggested by A. A. KALINSKE that they are caused by the wake formed behind a sand-ripple on the bed, since they resemble the wake formed behind a ship rather than a vortex. Perhaps this method of sediment-transport should be called "ripple-wake suspension".

The action differs from the ordinary form of bed-movement in which the sediment is rolled up the upstream slightly upward-sloping face of a ripple and over the ripple-crest, where it rolls down the steep downstream face. In this case, it rolls up the upward-sloping face to the point of the ripple where it is picked up by the upward current and taken into suspension and sinks back onto the bottom over a considerable area downstream. The ordinary form of bed-movement probably occurs in the stream at the same time, the upward currents occurring only from certain of the downstream slopes where the conditions are favorable.

The amount of material moved by the upward currents in the Canadian River was surprisingly large, probably much larger than would be carried under similar conditions by the usual transportation-methods. Pictures taken with the very cloudy weather at the time of observation show distinctly the mottled appearance of the water caused by the sediment in these vertical currents thickly scattered over the stream. In the Canadian River the depth of flow was about two feet, and in the Root River about one foot. The general slopes of these two rivers in the vicinities observed are about 3.0 and 2.4 feet per mile, respectively. The median size of the bed-materials was probably 0.27 and 0.50 mm respectively, but in the Root River particles probably as large as two mm appeared to be moved. It was recently observed in the Canadian River where the average depth was 5.3 feet and velocity 2.0 feet per second.

The measurement of sediment-discharge where this method of transport was active would seem to be very difficult, as the samples taken at one point would show many times the concentration of another at the same depth a short distance away, or in the same vertical at a slightly different depth.

When the water is clear this method of transportation would be clearly visible, but in muddy water it can be detected by the stationary position of the "boils" where these ripple-wakes reach the surface.

Circumstances prevented the writer from making the detailed study of these phenomena which he would otherwise have done, but it is hoped that this description will stimulate other observations which will more completely describe the phenomena.

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MOVEMENT AND DEPOSITION OF SEDIMENT IN THE VICINITY OF DEBRIS-BARRIERS

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Accelerated erosion and the scour and deposition of sediment in streams have had, in many instances, harmful effects on the use of valley-floors as residential areas and for farming and grazing. Perhaps the outstanding significance of streams carrying a relatively large sediment-load is the effect on the silting of large reservoirs, the silting-rates of which determine not only the life of these reservoirs for flood-control purposes, but also the perpetuity of agriculture, cities, and industries, which are dependent on the water stored.

In the past decade a large number of low dams or barriers of various designs have been constructed on many small streams located primarily in the western part of the United States. These structures act as barriers behind which sediment is deposited or held in place; however, in certain instances, they have been used also for the purpose of water-spreading to conserve for plant-production the water that otherwise would be lost [see 5 of "References" at end of paper]. The practice of water-spreading is probably limited to the sheer-banked arroyos which dissect many of the broad alluvium-filled valleys in northern Arizona and New Mexico. These barriers cause the arroyos eventually to become filled with erosional debris, and flood-waters spread over the adjacent valley-land. The effect of the barriers thus is to promote increased vegetative growth in the flooded areas on the flood-plain, as well as to reduce the amount of sediment which might deposit in and damage large reservoirs or cultivated and improved property downstream.

The design and construction of a debris-barrier must be based on the hydraulic and sediment-load characteristics of the particular stream. A consideration of the laws of transportation and deposition of sediment is of fundamental importance in estimating the effectiveness of any proposed barrier. That such estimates be as accurate as possible is especially necessary where barriers are intended to protect densely populated areas as in the vicinity of Los Angeles, California [7]. To aid in the design of a series of barriers that were proposed for the Arroyo Seco near Pasadena (Fig. 1), the United States Forest Service conducted a program of model-studies in cooperation with the University of California, Berkeley. These studies have been described in detail elsewhere [1] and are not summarized in this paper. The results of these model-studies, however, are the primary source of the principles discussed below.

When a dam is constructed on a stream, changes occur in the hydraulic and sedimentary regime of the stream. The hydraulic adjustments may be estimated fairly accurately from established principles, but the conditions resulting from deposits of sediment, which moved unhindered before construction of the dam, are now difficult to predict.

The initial, intermediate, and final effect of obstructing a stream by a low dam has been discussed by HARRIS [4]. Essentially his argument is as follows: The ponding of water behind a dam will cause sediment in transportation to come to rest and be distributed throughout the length of the reservoir as well as in the stream-channel within the limits of the backwater-curve. The amount and rate of the deposition at various points depends upon the age of the structure, the character and distribution of currents, the hydraulic properties of the stream, and, particularly, upon the size and specific gravity of the sediment. With fluctuations in discharge not only does the quantity of sediment of various sizes in the stream change, but also the locus of deposition may change over the entire limit of the backwater-curve. Eventually the upstream-bed elevations are increased to such an extent that the slopes of the newly formed river-bed will differ very little from the original slope of the particular stream. After this condition is attained, the reservoir ceases to exist, deposition almost ceases, and a normal movement of sediment down the river and over the dam is again established. Ultimately, not only will the stream-bed in the reach above the dam be shifted nearly parallel to the original slope of the river-bed, but the river-channel will lie in alluvial deposits of the same coarseness as the alluvium which existed prior to construction of the dam.

If the above argument is correct, the time required after the construction of a dam for the channel to fill and for the bed to assume a position above and nearly parallel to the original bed will depend primarily on the height of the dam, the character of the sediment-load, and the stream-discharge. In regions where the stream-flow is continuous throughout the year the time of filling may be relatively short because of the steady supply of material which constantly is moving downstream. In arid country, however, streams, as a rule, flow only a few days each year or once every few years so that the total load transported may be small and the time of filling consequently may be relatively long.

Fig. 1--Brown Canyon Barrier, Arroyo-Seco Flood-Control Project (Photograph during storm of January 21-24, 1943, U. S. Forest Service)

In regard to slopes obtained in the Arroyo Seco model-studies, it was found to be impractical, from a consideration of time and expense involved, to attain equilibrium-conditions by operating the model until the quantity of sediment passing over the crest of the barrier equals the quantity introduced at the upper end of the model. However, debris-runs were carried on until these quantities were relatively close to being equal and slopes up to 90 per cent of the original stream-bed were obtained.

Profile surveys by KAETZ and RICH [6] on the deposits above 22 barriers that ranged in age from one to 48 years failed to show that the average slope of the deposits approached even approximately the slope of the original stream-bed. Such observations seem contrary to the above reasoning of HARRIS or results of the model-studies, that a shift in the position of the upstream channel-bed, nearly parallel to the original bed, will occur. Actually the shift may eventually occur, but only after a relatively long period of time. The reason for the long time involved may be explained by the following considerations.

Soon after construction of a barrier a rapid rate of deposition occurs, because practically all material (bed and suspended) in movement, comes to rest in the basin created by the structure (Fig. 2). The occasional flows in most western streams carry high sediment-concentrations which are sufficient to fill a relatively small basin almost to spillway-level during one or two floods [5,6].

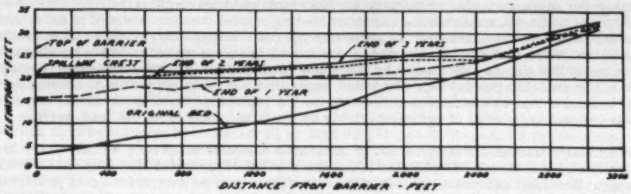

Fig. 2--Typical distribution of sediment behind debris-barrier (from surveys of Kaetz and Rich)

The slope of these earlier deposits varies with the average grain-size of the sediment. The slope of the deposits is initially flatter than that of the original stream because the deposited material, consisting of both bed-load and suspended load, is finer than the bed-load material of the original stream. The only manner in which a permanent new position of the bed can be formed at a slope parallel to the original bed is by deposits of material at least as coarse as the original bed-load material, other factors of course remaining the same. Eventually then, the bed may be elevated, but only as rapidly as the supply of coarse material moves down from upstream sources. It is the difference in velocities at which materials of different sizes are transported that accounts for the slow rate of grade-readjustment; that is, materials small enough to be carried in suspension are transported at practically the same velocity as the water which can be measured in units of feet per second. On the other hand, the bulk of relatively coarse material which moves by rolling and sliding along the bed is transported very slowly and over a long period of time at an average velocity that, for convenience, must be measured in feet per day or perhaps some larger unit. The final adjustment of grade can proceed, therefore, only as rapidly as the supply of coarse material is available. In arid regions where flows capable of transporting coarse material occur on the average no more often than a few times per year [5], the rate of sedimentation consequently may be relatively low.

In the usual barrier, whether it is located in a broad flat valley and used for water-spreading or whether it is in a narrow canyon such as the Arroyo Seco (Fig. 1), the width of the sediment-deposit behind the barrier usually increases as the basin becomes filled; consequently, a particular discharge is spread over a greater width than without the barrier in place. The effect of this lower discharge per unit-width, as sedimentation progresses, is that the sediment-transporting capacity per unit-width is decreased; consequently, in the actual barrier a finer material than that in the original stream-bed can exist at the same slope as the original profile. This principle would tend to shorten the time required for final grade-adjustment, since some of the finer fractions of the bed-material, which otherwise might be transported through the basin, would contribute to the deposits.

Measurements of the sediment-load of natural streams [3] have shown that where a stream flows over an alluvial bed (that is, the supply of bed-sediment is practically unlimited) there is a definite relationship between load and discharge. If in a certain reach of a stream the supply of bed-load at the upper end is sufficient to replace that transported out at the lower end, the position of the bed will remain relatively stable in its position, despite the fact that bed-load may be moving over the bed at a relatively high rate of transportation. Further, if for any reason the incoming supply is reduced, or intercepted completely, the stream will continue to transport bed-load at capacity; however, since no material is being supplied to the upper end of the reach to replace that transported out at the lower end, the position of the bed will be lowered progressively, or the bed will be said to be scoured. These general principles governing the transportation of bed-load were found to apply to the results of the model-studies on the Arroyo Seco debris-barriers, the nature of the Arroyo Seco being such that at times the supply of bed-material appears to be insufficient for the stream to maintain a capacity-load. Thus, with a particular sequence of discharges in the model that were repeated over and over and sufficient sediment introduced such that a capacity-load existed at all times, a certain equilibrium debris-slope was finally obtained which for practical purposes could be considered to be the equilibrium-slope. When less sediment was introduced than that required for capacity-loading, for the same sequence of discharges, the slope near the upper end of the deposits was found to be less than that for capacity-loading, and in the vicinity of the barrier the slope remained practically the same as for complete loading. These results were found to be consistent whether for a single barrier or for a series of barriers.

Even though the stream on which a barrier (or barriers) is to be constructed may not have a sufficient supply of sediment available for capacity-loading, model-studies intended to determine the probable debris-slope above the barrier should be operated at capacity-loading. This method gives the maximum slope that can be expected to occur and, hence, a measure of the maximum amount of sediment that can be expected to be stored by the barrier. To determine debris-slopes when operating the model at partial capacity would imply that the model-operator is able to predict the supply of sediment that can be expected to occur on the particular stream--a virtual impossibility with our present knowledge of sediment-yields by surface-runoff from the land-surface.

On streams which transport relatively large quantities of sediment, it may be necessary to construct a series of barriers to effectively reduce the amount of sediment that may cause downstream damage. The most desirable spacing of the barriers would be determined on a profile of the stream as follows: Starting with the barrier farthest downstream, a line is drawn from the crest of the barrier and at a slope equal to the maximum equilibrium-slope of the debris. The point where the line of maximum slope intersects the original stream-bed indicates the most desirable location of the next upstream barrier. The selection of the final location will depend, of course, upon the foundation-conditions and those factors which give the most economical structure. This procedure is repeated for the other barriers upstream. The maximum slope referred to above may be determined by model-studies or by field-surveys on nearby existing structures. In the Arroyo Seco model-studies equilibrium-slopes equal to 90 per cent of the original stream-bed slope were obtained. In the surveys of KAETZ and RICH the average grade of deposition above barriers in alluvial washes was 37 per cent of the original grade and in heavy gravel washes the average grade was 49 per cent of that of the original grade. It is highly probable that these barriers have not as yet reached their equilibrium-condition.

In a series of barriers there is the choice between a large number of relatively low barriers or a fewer number of relatively high barriers. The selection of the best system is primarily a problem in economics, wherein the cost per unit-volume of sediment stored or retained above the barriers is to be a minimum for the chosen quantity of material to be stored or the chosen period over which protection is desired. The order in which a series of barriers is constructed in a mountainous terrain like the Arroyo Seco may influence the efficiency of their operation. For example, it is possible to construct the first barrier at the lowest downstream site and proceed upstream with the construction of the subsequent barriers as the basins become progressively completely filled. It must be noted that in those basins which have become filled to an equilibrium-slope the position of the debris-surface will remain at this slope only as long as the supply of material entering the upper end of the basin is equal to the quantity being transported along the bed and over the barrier-crest. Should this supply of sediment be intercepted by an upstream barrier, the sediment existing in the basin will continue to be transported at a rate depending on the discharge. The consequent result will be that the deposits will be scoured and the slope flattened until a new equilibrium-slope is attained. This means that a certain quantity of sediment that has been intercepted by the barriers has been "picked up" again and transported downstream, perhaps to cause damage by sedimentation. The various downstream basins in which scour has taken place, due to the interception of the sediment-supply by the upstream barriers, will not begin to store sediment again until all the upstream basins have become completely filled to equilibrium and the downstream rate of sediment-movement is restored to normal.

Another choice in the order in which a series of barriers may be constructed is to start with the barrier farthest upstream and proceed downstream, building additional barriers only as the basins become progressively filled with debris. This method has the disadvantage that when the first barrier is constructed the normal downstream movement of sediment is intercepted and the stream-bed for the entire distance below the barrier is subject to scour. The consequent scour may in some instances cause more damage than that caused by the normal sediment-load moving on the more or less stable original bed.

In the construction of the Arroyo Seco barriers the necessity of building the uppermost barrier in the main-channel-barrier series first was dictated by the steep, mountainous terrain which makes any upstream site virtually inaccessible once a barrier has been constructed. It would be desirable for the ordinary project to construct almost simultaneously a series of barriers because of the fact that funds usually are made available for the construction of the entire project in a relatively short period, and because costs of construction are less when equipment and experienced personnel can proceed immediately from barrier to barrier as each is completed.

The same general principles of barrier design discussed above for a mountainous terrain apply to problems encountered in water-spreading projects in broad, flat valleys. A large number of the

ephemeral streams in the Southwest now flow between vertical banks of alluvium, varying in height from a few to as much as 50 feet (such sheer-bank streams are commonly called arroyos in Arizona and New Mexico, and should not be confused with a proper name like Arroyo Seco). These channels accommodate discharges as great as any previous flows of record without overflowing their banks throughout much of their length, and hence rob the valley-floors of the flood-waters that they previously received [5]. Floods merely tend to deepen or widen the arroyos which continually grow headward into the undissected valley-floors or headwater-valleys and tributaries.

Strong arguments have been advanced by BRYAN [2] that in the last 60 years, since the widespread occupation of the region by white man, most of the arroyos either have developed or progressively enlarged. The consequences have been the lowering of ground-water levels, the destruction of grazing lands, and the production of most of the sediment-load of the streams. Hence, on such streams, the essential problem is to reverse the process of channel deepening or widening and to promote channel-aggradation.

The most rapid method of filling an arroyo is accomplished by constructing a series of barriers. The rate of filling, obviously, would be increased over that of a single barrier, because the very fine material, which comprises the largest percentage of the stream-load and which is available in large quantities, could be forced to deposit.

In those streams with relatively large drainage-basins, it may not be feasible to divert and spread flood-flows over valley-lands without water returning by overland flow to the arroyo at a point downstream from the barrier. Should flood-waters reenter an arroyo at such a downstream location, more serious erosion and damage would probably occur to the arroyo walls and valley-lands than if no barrier existed.

On a stream where the drainage-basin is so large that flood-volumes and duration are of such magnitude that all water cannot be disposed of by spreading, or prior rights downstream prevent it, a barrier must be constructed with an auxiliary spillway located so that excess overflow may pass the barrier and flow down the arroyo without serious local scouring of the downstream bed.

In these barriers in which flood-flows pass the barrier over a suitable spillway and continue down the arroyo-channel, retrogression of the downstream bed usually occurs for a considerable distance because the supply of relatively coarse material, which formed the original bed, has been intercepted by the barrier. For each type of bed-material and condition of discharge there is a definite slope that is stable for a given supply of sediment. Consequently, when the supply has been intercepted, the bed will continue to retrograde, possibly by removal of the finer-sized fractions, until the average grain-diameter of the bed-material becomes large enough so that the bed-slope will remain relatively stable for all but possibly the most extreme flood.

Unquestionably, special problems will arise in the design and operation of certain barriers; however, it is believed that the considerations of the laws of transportation and deposition of sediment, as discussed above, will be of general importance in predicting where scour and fill may be expected to occur in the vicinity of a proposed structure, or in explaining the reasons for scour or fill at certain locations in the vicinity of existing structures.

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DISCUSSION

CARL B. BROWN (Soil Conservation Service, Washington 25, D. C.)--The authors of this paper have performed a valuable service in clearly describing the principles involved in control of sediment-movement by debris-barriers. In southern California, in particular, where debris-barriers of various types have been widely used for years, many avoidable failures have been experienced as a result of lack of understanding of the hydraulic principles involved in transportation of bed-material. One of the most common mistakes has been to assume that the new equilibrium-slope between or above barriers would develop rapidly and would almost equal the original bed-slope. As a corollary the possibility of serious damage from bed-scour immediately below the structure was not fully appreciated.

Channel and arroyo debris-dams have two separate functions which should be clearly distinguished. One is to actually store debris for the purpose of decreasing the quantity that reaches some downstream point of damage. The second is to prevent bed-scour or the progress of headward erosion of the channel and to stabilize the side slopes by reducing the opportunity for undercutting.

If a single debris-storage dam is constructed on a channel having a thick bed-deposit and highly erodible sides, such as characterizes many of the Western arroyos, it is entirely possible, if not probable, that the load of coarse sediment entrained by the desilted flow below the dam will equal the load trapped. Usually the coarse bed-material is the primary source of downstream damage. A serious question would therefore arise as to the desirability of constructing a series of barriers progressively downstream. In the case of the Brown Canyon Barrier on the Arroyo Seco, however, the main purpose is to protect the Devils Gate Flood-Control Reservoir, located on the fan beyond the mountain front and hence if the total load trapped is in excess of the new bed-load entrained, the net effect is beneficial.

Another effect of desilting of the flow by a debris-barrier is the hazard of undercutting the toe of the structure. Many failing structures can be found in southern California with their aprons several feet above the present channel-bed, or the wing-walls suspended in air by scouring side-eddies. Desilted water in steep canyons and arroyos has a powerful affinity for any material that is loose or can be loosened. Much progress has been made in the past several years at the Cooperative Laboratory of the Soil Conservation Service and California Institute of Technology, Pasadena, in perfecting designs for scour-prevention in channel-control structures. The best possible design, however, cannot prevent the ultimate undermining of a structure, not founded on solid rock, where steep bed-slopes and loose material are met by energy-filled desilted flows.

Much point has been made in southern California of the effect of debris-barriers, or rather the ultimate deposits behind them, in stabilizing the very steep and inherently unstable side-slopes of the coastal ranges. If landslides, slumping, and soil-creep down these slopes are substantially reduced by the deposits behind debris-dams, the rate of sediment-production into the channels will be materially lessened, quite irrespective of the quantity of debris that may be impounded behind the dam. There is little doubt that the backfilling of sediment against the slopes tends to buttress them and the spreading of flow across the wider area of deposits, reduces its velocity and minimizes undercutting. It is not agreed, however, that any amount of support at the base of the slope can prevent excessive downslope movement once the soil is saturated and lubricated.

Since major reliance for control of debris-damages must be placed on debris-barriers and similar works in many parts of the West, there is an urgent need for both laboratory investigations such as those made in connection with the Brown Canyon Dam, and for critical field-study of the effects of existing barriers.

RECTANGULAR ARTIFICIAL ROUGHNESS IN OPEN CHANNELS

J. W. Johnson

Introduction--Numerous experiments on artificial roughness in closed channels have been made in Europe and the United States since about 1920: In Europe, SHILLER [see 12 of "References" at end of paper] experimented with pipes roughened with spiral threads cut into the inner surface; HOPF [6] and FROMM [5] investigated roughness in a rectangular closed conduit; NIKURADSE [8] investigated relative roughness over a wide range by gluing sand to the inside of pipes; and SCHLICHTING [10] experimented with a closed conduit roughened with various arrangements of spheres, spherical segments, cones, short and long angles, and sand. A brief discussion

of the results of the work of SHILLER, HOPF, FROMM, and NIKURADSE may be found in the paper by STREETER [15]. The more recent investigation of SCHLICHTING has been translated into English by the National Advisory Committee for Aeronautics and published as a Technical Memorandum [11].

In the United States, the earliest experiments with closed conduits using water were made by FREEMAN [4]. More recently, experiments have been made by STREETER [15] and SKOGLUND [13] using water and by TRIPP [16] using air. The early experiments of FREEMAN were made by fastening metal lath and rubber hemispheres to the interior of a pipe. The investigation by STREETER was made on pipes roughened by spiral grooves with triangular, rectangular, trapezoidal, and wavy sections. The experiments by SKOGLUND were made in rectangular channels roughened by 60° v-grooves transverse to the direction of flow. TRIPP made an investigation similar to that of SKOGLUND but used air in wooden rectangular closed conduits roughened by saw cuts transverse to the direction of flow. FOLSOM [3] with the aid of photography has discussed the flow-pattern in the vicinity of ultra-rough surfaces.

Except for the early experiments of BAZIN [1], little data on artificial roughness in open channels appear to be available. In his investigation, BAZIN nailed transverse wood strips (2.7 cm wide by 1 cm thick) to the bottom and sides of a rectangular flume. One set of experiments was made with a spacing of one cm and another set with a spacing of five cm. Thus, referring to Figure 1, the artificial roughnesses had a width-height ratio (b/a) of 2.7 and were spaced with the ratio (c/a) = 1 and = 5.

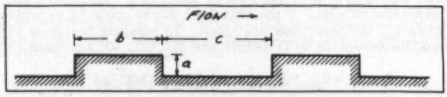

Fig. 1--Designation of dimensions of artificial rectangular roughness

In either an open or a closed channel with artificial roughnesses formed by rectangular strips of a certain size placed transverse to the direction of flow, it is to be noted that as the spacing c (Fig. 1) or the ratio (c/a) becomes small, the surface-roughness of the channel approaches that of the surface-roughness of the strips. Also, when the spacing c or the ratio (c/a) becomes very large, the roughness-coefficient approaches that of the channel without the strips. Therefore, at some intermediate value of the ratio (c/a), the roughness-coefficient must be a maximum. The purpose of the present investigation was to determine, for strips with a particular width-height ratio [(b/a) = 4], the value of the ratio, (c/a), at which the roughness-coefficient for the channel was a maximum.

Apparatus and experimental procedure--A redwood flume approximately 9-1/2 by 9-1/2 inches in cross-section and 70 feet long, located in the Hydraulic Laboratory of the University of California, was used in these experiments. The interior of the flume was painted with a gloss finish and had an average width of 0.785 foot. At the upper end of the flume a three-foot by three-foot forebay was located and provided with baffles to "still" the flow. At the lower end the water discharged by free overfall into an afterbay and then flowed into the sump. Water was supplied to the flume by first pumping from the sump into a constant-head tank. A six-inch pipe-line, containing a six-inch by four-inch Venturi meter for measuring the discharge, connected the constant-head tank with the forebay of the flume.

Sixteen stations were located along the channel for determining the position of the water-surface. The stations were numbered from the upper end of the channel. Stations 1, 2, and 3 were 2-1/2 feet apart; stations 4 to 14 inclusive were 5 feet apart; and stations 14, 15, and 16 were 2-1/2 feet apart. Measurement of the position of the water-surface by means of a movable point-gage, therefore, could be made over a distance of 65 feet. A profile of the bottom was made with a surveyor's level and rod. The average bottom slope, S_o, was found to be 0.00245. All experiments were made with the flume at this slope.

The rectangular artificial roughness used through the investigation was made by nailing one-inch by one-quarter-inch redwood strips to the bed of the flume transverse to the direction of flow. The strips had the original smooth finish of the planing-mill and were given a coat of water-proof

Table 1--Description of roughnesses tested

Designation roughness	Spacing, c	(c/a)
	in	
A	1	4
B	3	12
C	7	28
D	1 1/2	6
E	4	16
F	2	8
G	5	20
H	2 1/2	10
I	3 1/2	14

varnish after being cut to the proper length. Ratios of (c/a) varying from 4 to 28 were obtained by making the spacing between strips as shown in Table 1. The irregularity of the order in which the values of (c/a) occur may be explained, as an example, by noting that the spacing of strips for Roughness B was obtained by removing the alternate strips that gave Roughness A. Similarly, removal of alternate strips for Roughness B gave Roughness C.

With each particular spacing of strips in the flume, the experimental procedure consisted of observing the water-surface position for an average of 11 different discharges during which the depth varied from about 0.3 foot to about 0.6 foot. The depth in all cases was measured to the top of the strips. Actually, the true depth would probably be somewhere between this depth and the depth to the bottom of the valleys between strips. The roughness-coefficient as calculated below by using the depth to the top of the strips is least affected at the larger depths and most affected at the lower depths. As previously mentioned, the discharge was measured by means of a calibrated Venturi meter located in the supply-line to the flume. For the nine roughnesses listed in Table 1 a total of 101 runs were made.

Experimental data--From the set of point-gage readings on the water-surface during a run the water-surface profile was plotted as illustrated by the typical runs shown in Figure 2. That portion of the profile above the influence of the drawdown-curve could be represented as a straight line and was designated as S_w, the water-surface slope. To compute the slope of the energy-grade line the varied flow-equation developed by O'BRIEN and HICKOX [9] was used as in equation (1).

$$(dy/dx) = S_0 - (Q^2/C^2A^2R)/[1 - \alpha(BQ^2/gA^3] \quad \ldots\ldots\ldots\ldots\ldots \quad (1)$$

where (dy/dx) = the change in depth with distance along the flume, S_0 = bottom slope, Q = discharge, A = cross-sectional area, B = width of flume, C = CHEZY coefficient, R = hydraulic radius, g = acceleration of gravity, and α = velocity-head correction (assumed = 1.05, from published data on flow in straight flumes). If S_w and S_e are the slopes of the water surface and energy-grade line, respectively, then $(dy/dx) = -(S_w - S_0)$ and, noting that $S_e = Q^2/C^2A^2R$, equation (1) reduces to equation (2).

$$S_e = S_w - (\alpha Q^2/gb^2d^3)(S_w - S_0) \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

For the observed depth, d, at Station 7, (Fig. 2) the slope of the energy-grade line was computed by equation (2).

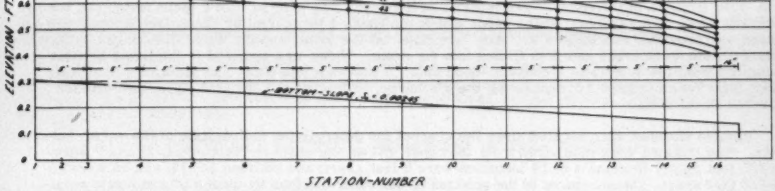

Fig. 2--Water-surface profiles for a typical set of runs

Since the roughness-strips were nailed only to the bottom of the flume, the roughness-coefficient (such as MANNING'S n) would vary with the depth. To eliminate the effect of the friction along the flume-walls and obtain the roughness-coefficient of the bed alone, the following method of EINSTEIN [2] was used.

From the preliminary experiments with no roughness-strips in the flume, the value of the MANNING n of the smooth channel was found to be 0.0091. With values of n_w, S_e, B, d, and mean velocity, V, given, the hydraulic radius of a side wall is as in equation (3).

$$R_w = (Vn_w/1.486\, S_e^{1/2})^{3/2} \quad \ldots\ldots (3)$$

From equation (3) the area for flow along the side-wall is as in equation (4).

$$A_w = R_w d \quad \ldots\ldots (4)$$

The area for flow along the bed is hence as in equation (5).

$$A_b = (A - 2A_w) \quad \ldots\ldots (5)$$

The hydraulic radius of the bed is

$$R_b = (A_b/B) \quad \ldots\ldots (6)$$

and the MANNING coefficient of the bed is

$$n_b = (1.486\, R_b^{2/3} S_e^{1/2}/V) \quad \ldots\ldots (7)$$

In order to compare the results of these experiments with the data of other investigators in which the "equivalent sand-roughness", k, of NIKURADSE was computed instead of the MANNING coefficient, the value of k for each of the various roughnesses was calculated from the equation (8) of NIKURADSE for flow in circular pipes.

$$(1/\sqrt{f}) = 2 \log_{10}(r/k) + 1.74 \quad \ldots\ldots (8)$$

where f is the friction-factor and r is the pipe-radius. Noting that r may be replaced by $2R_b$, equation (8) becomes

$$(1/\sqrt{f}) = 2 \log_{10}(2R_b/k) + 1.74 \quad \ldots\ldots (9)$$

where

$$(8\tau/\rho V^2) = 8gR_b S_e/V^2 \quad \ldots\ldots (10)$$

in which τ is the shear-force per unit-area of the bed and ρ is the density.

Table 2--Summary of observed and calculated data for roughness D
(Flume-width = 0.785 foot)

Run	Water temp.	d (Sta.7)	Q	V	S_e	R_o	n_b	f	k
	°C	ft	cfs	ft/s		ft			ft
37	66	.516	.915	2.26	.00339	.364	.0196	.0622	.0540
38	66	.490	.845	2.19	.00323	.348	.0191	.0603	.0482
39	66	.460	.755	2.09	.00317	.334	.0193	.0623	.0495
40	66	.424	.660	1.98	.00308	.314	.0192	.0632	.0483
41	66	.385	.555	1.83	.00313	.298	.0203	.0715	.0581
42	66	.347	.470	1.72	.00302	.274	.0200	.0716	.0535
43	65	.510	.920	2.30	.00334	.357	.0188	.0580	.0451
44	65	.500	.875	2.23	.00329	.352	.0192	.0600	.0479
45	65	.477	.815	2.18	.00320	.339	.0188	.0587	.0437
46	65	.454	.755	2.12	.00325	.330	.0191	.0617	.0478
47	65	.424	.650	1.95	.00330	.321	.0206	.0718	.0650
48	65	.382	.570	1.90	.00293	.285	.0184	.0595	.0389

Averages: n_b = .0194; k = .0500

The summary in Table 2 of observed and calculated data for the runs on Roughness D is typical of the general range in variation of the values of the various quantities. A summary of the averages of the values of the MANNING coefficient, n_b, and the equivalent sand-roughness, k, for

Table 3--Summary of equivalent sand-roughness for rectangular artificial roughnesses

Designation roughness	Dimensions			(b/a)	(c/a)	k	n_b
	a	b	c				
	in	in	in			ft	
A	1/4	1	1	4	4	.0202	.0163
B	1/4	1	3	4	12	.1297	.0244
C	1/4	1	7	4	28	.0698	.0208
D	1/4	1	1.5	4	6	.0500	.0194
E	1/4	1	4	4	16	.1185	.0236
F	1/4	1	2	4	8	.1050	.0229
G	1/4	1	5	4	20	.0940	.0223
H	1/4	1	2.5	4	10	.1255	.0240
I	1/4	1	3.5	4	14	.1270	.0240
Smith and Warren							
A	1/8	5/32	5/32	1.25	1.25	.0022	.0112
B	1/8	5/32	15/32	1.25	3.75	.0432	.0185
C	1/8	5/32	35/32	1.25	8.75	.0525	.0200
D	1/8	5/32	75/32	1.25	18.75	.0313	.0170
E	1/8	5/32	155/32	1.25	38.75	.0125	.0149
Tripp (air)	1/8	1/2	1/8	4	1	.000652	.....
Jonassen (air)							
1	1/8	3/16	1/8	1.50	1	.00176	.....
2	1/8	1/8	1/2	1	4	.0264	.....
3	1/8	1/8	1-1/8	1	9	.0575	.....
4	1/8	1/8	2-3/8	1	19	.0364	.....
5	1/8	1/8	4-3/8	1	35	.0155	.....
Bazin (closely spaced)	0.394	1.063	0.394	2.7	1	.0135	.....
Bazin (widely spaced)	0.394	1.063	1.970	2.7	5	.1102	.....

the various roughnesses is given in Table 3. Figure 3 shows a plot of the average n_b against the ratio (c/a) for each roughness. Also shown in this Figure is the range in values of n_b. The maximum roughness appears to occur when the ratio (c/a) = 12; however, it is to be noted that the curve through the plotted points is rather flat in the region from $10 < (c/a) < 14$. In Figure 4 is shown a plot of the equivalent sand-roughness, k, against the ratio (c/a).

Other investigations--In addition to the published investigations by BAZIN, SKOGLUND, and TRIPP, certain unpublished experiments on artificial rectangular roughness made at the University of California are available for comparison with the data summarized in Figure 3. Using the apparatus of TRIPP, F. JONASSEN made experiments with five different ratios of (c/a) by removing alternate ridges between saw cuts. SMITH and WARREN [14] used the same flume as described in the present experiments, except that instead of nailing strips to the channel-bottom removable redwood-planks, with saw cuts, were fastened to the flume-bottom. The roughness was changed by removing alternate ridges formed by the saw cuts. A summary of all the known data on artificial rectangular roughness is given in Table 3. Included in this summary are the dimensions of the roughness-ridges, the ratios (c/a) and (b/a), the equivalent sand-roughness, and the MANNING roughness-factor. The value of k for the BAZIN data has been calculated previously by KEULEGAN [7]. A plot of k against (c/a) for all the various investigators is shown in Figure 4.

Only the experiments reported in this paper appear to contain sufficient information to permit determination of the approximate value of the ratio (c/a) at which the roughness-coefficient is a maximum. The trend of the data of JONASSEN and SMITH and WARREN, however, appears to indicate that the maximum value of k would also occur in the neighborhood of (c/a) = 12. For flow in an annular section with an ultra-rough surface on a concentric core and with the dimension b small in comparison with the spacing c, FOLSOM [3] found that maximum friction occurred when (c/a) = 4. The various data are not complete enough to draw any conclusions regarding the relative locations of the curves in Figure 4 as a function of the ratio (b/a). It is interesting to note, however, that the curves of TRIPP and JONASSEN [where (b/a) = 1 and air was the fluid] do not differ, within the limits of experimental variation, from the curve of SMITH and WARREN where (b/a) = 1.25

and water was the flowing fluid. Just as was reasoned in the introduction that for a particular rectangular roughness (that is, with the ratio (b/a) constant) there is a value of (c/a) at which the roughness-coefficient is a maximum, it also can be reasoned that with constant values of b and c there should be some value of a to give values of (c/a) and (b/a) at which the roughness-coefficient is a maximum. That the ratio of (b/a) for maximum roughness may lie somewhere between a value of 1.25 (as used in the experiments of SMITH and WARREN) and a value of 4 (as used in the

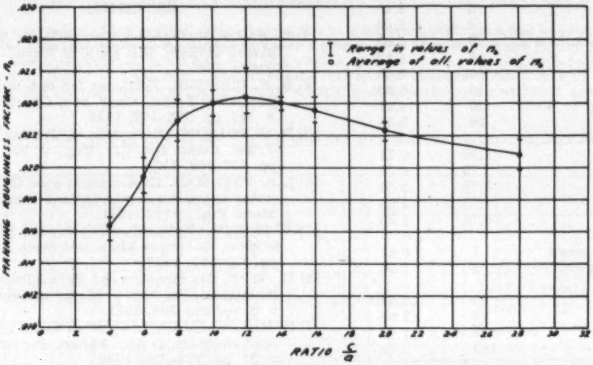

Fig. 3--Manning roughness-factor as a function of the ratio c/a

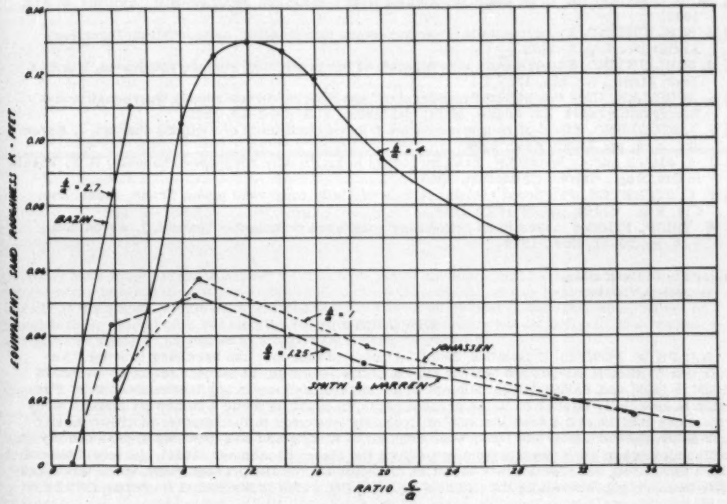

Fig. 4--Equivalent sand-roughness, k, as a function of ratio c/a, from the data of various experimenters

Table 4--Equivalent roughness found by different observers

Designation	(c/a)	(k/a)
Johnson's		
A	4	0.97
D	6	2.40
F	8	5.04
H	10	6.02
B	12	6.23
I	14	6.10
E	16	5.69
G	20	4.51
C	28	3.35
Smith and Warren		
A	1.25	0.21
B	3.75	4.15
C	8.75	5.04
D	18.75	3.00
E	38.75	1.20
Bazin		
Closely spaced	1	0.41
Widely spaced	5	3.36
Powell		
III, VII	19	3.89
II, VIII	39	2.60
I, IX	79	1.40
X, XI	159	0.72

present experiments) is indicated by the plot of BAZIN'S data in Figure 4 where the only two points available, in which (b/a) = 2.7, lie above the other two curves. Experiments on roughness with values of (b/a) between 1 and 4 would be of value in checking the indications of BAZIN'S data.

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DISCUSSION

RALPH W. POWELL (Columbus, Ohio)--A paper of this sort has been long overdue. As Professor JOHNSON has pointed out, the only published work on the subject seems to be that of BAZIN in 1865, and BAZIN did not attempt to go into the question in any fundamental way. The writer is especially interested in the present paper, because he made a somewhat similar study of the same subject at the Iowa Institute of Hydraulic Research in the summer of 1940. After much delay, the results of that study were reduced to writing and will probably appear shortly in the Proceedings of the American Society of Civil Engineers [December, 1944]. As four different slopes were used, and also a wider variation of depths than in the present study, there was opportunity to check experimentally the author's equation (9), which is equivalent to putting CHEZY'S

$$C = 32.08 \log (R_b/k) + 37.6 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (11)$$

It was found that the data did not fit this equation well at all, and that a much better form was

$$C = 40 \log (R_b/k) + J \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (12)$$

Letting $J = 40 \log (k/\epsilon)$ this becomes equation (13)

$$C = 40 \log (R_b/\epsilon) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (13)$$

where ϵ is a measure of the equivalent roughness, but to a different scale than that used by NIKURADSE. The data given by the author in Table 2 give a value of ϵ in equation (13) of 0.00968 foot with an average deviation of 8.5 per cent, and a value of k in equation (9) of 0.0500 foot with an average deviation of 10.2 per cent. The difference between the average deviations is not sufficient to establish the superiority of equation (13), but in the study made by the writer it was very definite.

However, the problem as to what spacing will give the maximum equivalent roughness would

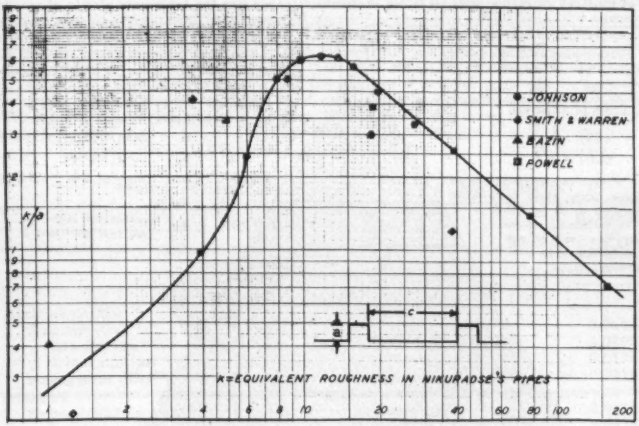


Fig. 5--Relation of rectangular roughness in channels to Nikuradse's sand-roughness in pipes

probably have about the same answer figured from either formula. Not having the author's data for the other roughnesses, it was impossible to check this, but the writer has reduced his own results to the author's form using the relation $k = 5.16\ \epsilon$ which held in the above computation of Roughness D. He has also reduced the roughness to the dimensionless form (k/a). The results are given in Table 4 and plotted to a logarithmic scale in Figure 5.

The author's method of correcting for the side-effect is clever, but there still remains the question whether there would not be a "shape-correction" as discussed by KEULEGAN [7].

The mathematics of equation (2) seems correct, but the writer believes it would have been better to have installed a tail-gate and adjusted to uniform flow each time before taking readings. This would have taken more time for the observations but would have saved on the computation and given more trustworthy results. As B. A. BAKHMETEFF has shown [Coriolis and the energy principle in hydraulics, THEODORE VON KARMAN Anniversary Volume, Contributions to Applied Mechanics and Related Subjects, Calif. Inst. Tech., p. 59, 1941], we were all mislead into making our correction in the velocity-head to compensate for non-uniform velocity-distribution, three

times as great as it should have been. And in this case α was quite certainly practically one at entrance, and somewhat more at points downstream. It would seem, therefore, that a small systematic error must have resulted from taking α as 1.05 throughout.

A GRAPHIC PROCEDURE IN THE GEOCHEMICAL INTERPRETATION OF WATER-ANALYSES

Arthur M. Piper

General considerations--This paper outlines certain fundamental principles in a graphic procedure which appears to be an effective tool in segregating analytical data for critical study with respect to sources of the dissolved constituents in waters, modifications in the character of a water as it passes through an area, and related geochemical problems. The procedure is based on a multiple-trilinear diagram (Fig. 1) whose form has been evolved gradually and independently by the writer during the past several years through trial and modification of less comprehensive antecedent forms. Neither the diagram nor the procedure here described is a panacea for the easy solution of all geochemical problems. Many problems of interpretation can be answered only by intensive study of critical analytical data by other methods.

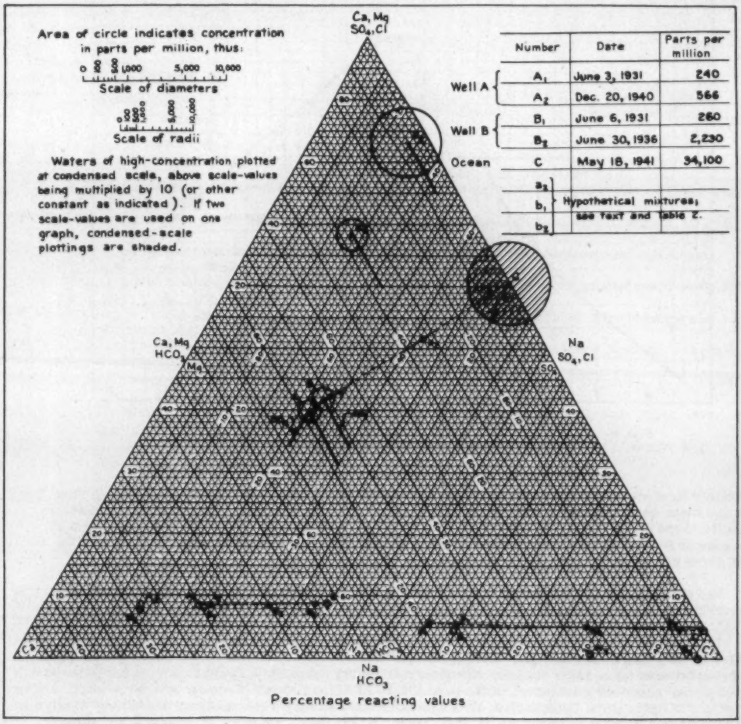


Fig. 1--Water-analysis diagram

In certain respects the diagram is analogous to, but in other respects differs fundamentally from, the "geochemical chart" described recently by HILL [see 1 of "References" at end of paper] and from the "water classification diagram" described by LANGELIER and LUDWIG [2]. As presented in Figure 1, the diagram is the mirror image of a prototype which in 1942 was circulated among colleagues in the United States Geological Survey and other coworkers in hydrology; thus, it conforms substantially to LANGELIER'S adaptation [3] of HILL'S diagram and to the conventional practice of arranging diagrams of water-analyses with cations shown to the left of the anions. Some details in Figure 1 embody adaptations which serve constructive criticisms of the prototype by colleagues and coworkers; for these criticisms the writer is grateful.

Most natural waters contain relatively few dissolved constituents, with cations (metals or bases) and anions (acid radicles) in chemical equilibrium with one another; commonly the waters contain some silicon, iron, and aluminum but these constituents are usually assumed to occur in the colloid state as oxides and not to be in chemical equilibrium with the ionized constituents. Ordinarily the most abundant cation constituents are two "alkaline earths", calcium (Ca) and magnesium (Mg), and also one "alkali", sodium (Na). Potassium (K) also occurs commonly, but ordinarily is much less abundant than sodium. Still other cation-constituents occur in appreciable quantities in highly concentrated natural waters and in some waters of unusual composition. For the graphic methods treated in this paper all these less abundant constituents are summed with the major three constituents to which they are respectively related in chemical properties, as indicated by the two ranks of entry in Table 1. The most common anion-constituents are one "weak acid", bicarbonate (HCO_3); also two "strong acids", sulphate (SO_4) and chloride (Cl). Less common anion-constituents are listed in Table 1; for plotting, these are summed with the major three anions to which they are respectively related. Thus, for much of the graphic methods here described, a natural water is treated substantially as though it contained only three cation-constituents and three anion-constituents.

Table 1--Common and minor constituents of natural waters

Cations	Reciprocal of combining weight	Anions	Reciprocal of combining weight
Alkaline earths		Weak acids	
Calcium (Ca^{++})	0.04990	Bicarbonate (HCO_3^-)	0.01639
Barium (Ba^{++})	0.01456	Carbonate ($CO_3^=$)	0.03333
Strontium (Sr^{++})	0.02282	Tetraborate ($B_4O_7^=$)	0.01288
Magnesium (Mg^{++})	0.08224	Orthophosphate ($PO_4^{\equiv}$)	0.03157
Alkalies		Strong acids	
Sodium (Na^+)	0.04348	Sulphate ($SO_4^=$)	0.02082
Potassium (K^+)	0.02558	Chloride (Cl^-)	0.02820
Caesium (Cs^+)	0.00752	Iodide (I^-)	0.00788
Rubidium (Rb^+)	0.01170	Bromide (Br^-)	0.01251
Lithium (Li^+)	0.14409	Fluoride (F^-)	0.05263
Ammonium (NH_4^+)	0.05543	Nitrate (NO_3^-)	0.01613
		Nitrite (NO_2^-)	0.02174

Notes: Of the second-rank constituents only potassium, carbonate, fluoride, and nitrate are commonly determined in a "complete" analysis. Reciprocals of combining weights are based on the international atomic weights of 1938.

In substantially all natural waters the cations are in chemical equilibrium with the anions. Accordingly, if the concentrations of the several dissolved constituents are measured in terms of percentage of reacting value--that is, according to their "equivalents per million" expressed as a percentage of the sum of the equivalents for all the constituents [the concentration of any constituent in equivalents per million (milligram equivalents per kilogram) is computed by multiplying its concentration in parts per million by the reciprocal of its combining weight]--the subtotals of the cations and anions are necessarily each 50 per cent of the whole.

Thus, to the extent that a natural water can be treated in terms of three cation-variables and three anion-variables, as has been outlined, and because the subtotals of its cations and anions are

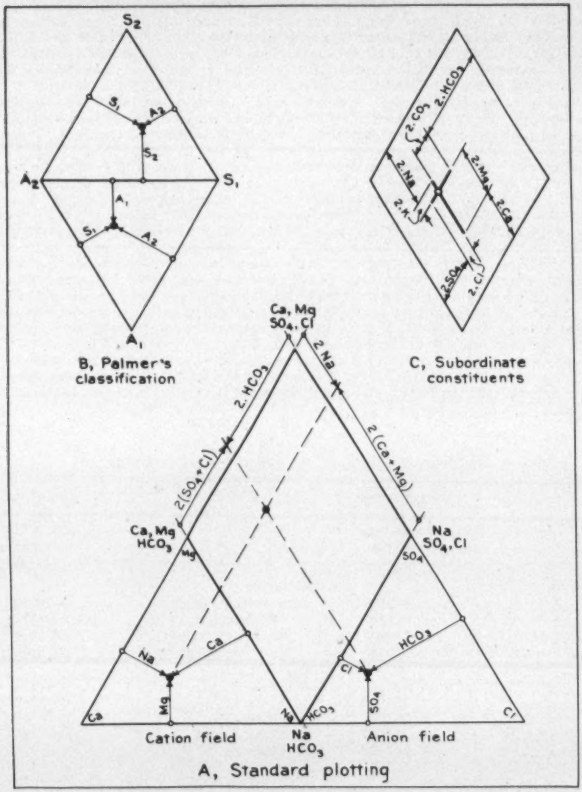


Fig. 2--Plotting key for water-analysis diagram (In diagram B, A_1 indicates primary alkalinity or "carbonate alkali", A_2, secondary alkalinity or "carbonate hardness", S_1, primary salinity or "non-carbonate alkali", S_2, secondary salinity or "non-carbonate hardness")

each 50 per cent of the total reacting value, the essential chemical character of the water can be indicated graphically by single-point plotting on trilinear coordinates. This is the basis of the diagram herein described.

Methods of plotting

The diagram herein described combines three distinct fields for plotting--two triangular fields at the lower left and lower right, respectively, with percentage scales reading in 50 parts; also an intervening diamond-shaped field with scales reading in 100 parts (see Figs. 1 and 2-A). In the triangular field at the lower left, the percentage reacting values of the three cation-groups (Ca, Mg, Na) are plotted as a single point according to conventional trilinear coordinates. The three anion-

groups (HCO_3, SO_4, Cl) are plotted likewise in the triangular field at the lower right. Thus, two points on the diagram--one in each of the two triangular fields--indicate the relative concentrations of the several dissolved constituents of a natural water.

The central diamond-shaped field is used to show the over-all chemical character of the water by a third single-point plotting, which is at the intersection of rays projected from the plottings of cations and anions as indicated on Figure 2-A. Using the scales of Figure 1, the position of this plotting indicates the relative composition of a water in terms of the cation-anion pairs that correspond to the four vertices of the field. This central-field plotting can also be taken directly from the analytical data according to the vectors shown along the outer margins of the field on Figure 2-A. For such plotting only one cation-variable and one anion-variable need be used--either alkaline earths or alkalies with either weak acids or strong acids; the two percentage reacting values selected from the analytical data are doubled to suit the numerical scales of Figure 1.

The three trilinear plottings just described will show the essential chemical character of a water according to the relative concentration of its constituents, but not according to the absolute concentrations. Because the absolute concentrations commonly are decisive in many problems of interpretation, it is convenient to indicate the plotting in the central field by a circle whose area is proportional to the absolute concentration of the water. Figure 1 shows such plottings for several dissimilar waters.

The diamond-shaped field of the writer's diagram is essentially a mirror image of LANGELIER'S diagram, sheared 30° to transform the latter from Cartesian to trilinear coordinates. Also, plottings in that field can be made or interpreted according to PALMER'S classification [4], as explained in the following paragraphs. This scheme of classification has many advantages but has not found universal favor, possibly because it implies certain specific combinations of dissolved constituents, which are hypothetical rather than real.

The classification by PALMER designates the alkaline cations (Na, K) as the "primary" constituents, the alkaline-earth cations (Ca, Mg) as the "secondary" constituents, the strong-acid anions (SO_4, Cl, NO_3) as the "saline" constituents, and the weak-acid anions (CO_3, HCO_3) as the "alkaline" constituents. It ascribes "primary salinity" to a water to the extent that the alkalies of that water are balanced by strong acids and "secondary alkalinity" to the extent that the alkaline earths are balanced by weak acids. Further, it ascribes "primary alkalinity" to the water to the extent that alkalies exceed strong acids and are balanced by weak acids, or "secondary salinity" to the extent that alkaline earths exceed weak acids and are balanced by strong acids. Because the latter two properties are mutually exclusive, a water can not possess both. Thus, the chemical character of most natural waters can be expressed by PALMER'S classification in terms of three hypothetical properties; in terms of percentage reacting value, the three must sum up to unity (analytical errors adjusted), of course. Accordingly, chemical character can be plotted as a single point with respect to trilinear coordinates.

A very few natural waters contain free acid in substantial quantity--that is, hydrogen is present as a cation; this cation PALMER designates as "tertiary". The chemical character of such waters can not be fully represented on the diagram.

If on the water-analysis diagram the two rays projected from the plottings of cations and anions intersect in the lower triangular half of the diamond-shaped field, the water has primary alkalinity (A_1), secondary alkalinity (A_2), and primary salinity (S_1) (see Fig. 2-B). Conversely, if the rays intersect in the upper triangular half of the field, the water has secondary salinity (S_2) rather than primary alkalinity.

Obviously, the plottings in the diamond-shaped field do not bring out critical ratios between certain constituents, such as the ratios between sodium and potassium, calcium and magnesium, carbonate and bicarbonate, or sulphate and chloride. When pertinent, these ratios can be indicated graphically by vectors that indicate four of the common eight constituents, as shown by Figure 2-C. In scaling these vectors, the percentage reacting values of the analytical data are doubled to suit the numerical scales of Figure 1.

With respect to the sources of dissolved constituents, or to progressive changes in chemical character within a particular area, many problems involve waters which differ only slightly in character or in which significant differences are masked by some common but preponderant constituent. Under such circumstances, the small differences in character can be emphasized by using the full diagram to represent proportionate subdivisions of the standard three plotting fields,

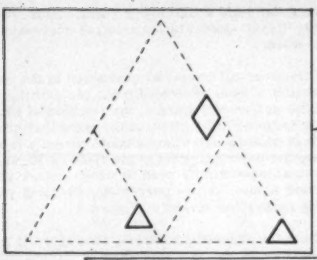
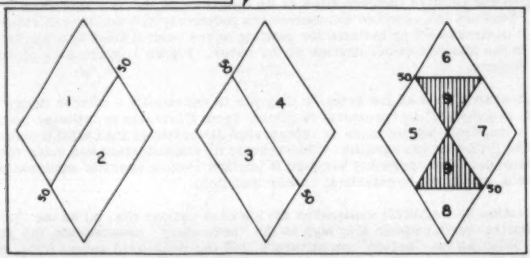


Fig. 3--Scheme of plotting by extended scales

Fig. 4--Subdivisions of the diamond-shaped field



and plotting the constituents with extended scales. For example, among brines similar to ocean water the minor constituents can be differentiated by plotting at five times the standard scale and using the full diagram to represent the small areas outlined in Figure 3. If desired, minor or accessory constituents can be so emphasized by vectors in the diamond-shaped field, as described in the preceding paragraph.

Differentiation of water-types

Certain distinct types can be quickly discriminated by their plottings in certain subareas of the diamond-shaped field, as indicated by Figure 4 and the following explanation: Area 1, alkaline earths exceed alkalies; Area 2, alkalies exceed alkaline earths; Area 3, weak acids exceed strong acids; Area 4, strong acids exceed weak acids; Area 5, secondary alkalinity ("carbonate hardness") exceeds 50 per cent--that is, chemical properties of the water are dominated by alkaline earths and weak acids; Area 6, secondary salinity ("non-carbonate hardness") exceeds 50 per cent; Area 7, primary salinity ("non-carbonate alkali") exceeds 50 per cent--that is, chemical properties are dominated by alkalies and strong acids--ocean water and many brines plot in this area, near its right-hand vertex; Area 8, primary alkalinity ("carbonate alkali") exceeds 50 per cent--here plot the waters which are inordinately soft in proportion to their content of dissolved solids; Area 9, no one of the cation-anion pairs in PALMER'S classification exceeds 50 per cent.

These subareas might serve as a basis for numerical or other symbols to designate specific classes, types, and subtypes of water. Symbols for this purpose have been introduced by PALMER [4] and HILL [1]; however the writer feels that inflexible classifications of this sort tend to confuse by over-emphasizing differences in composition that may not be significant to the problem under consideration.

To serve most needs for classifying waters by types the writer proposes--in lieu of symbols such as those introduced by PALMER, HILL, and others--to designate a water by a binomial symbol written in the form of a decimal fraction, whose two terms are (1) the percentage of hardness-causing constituents among the bases and (2) the percentage of bicarbonate (and carbonate, if present) among the acids. For example, the symbol 64.80 would indicate a water in which the hardness-causing constituents (Ca + Mg) amount to 64 per cent of all the bases, in terms of reacting values

(equivalents); also in which the weak acids (CO_3 + HCO_3) amount to 80 per cent of all the acids, in like terms. Numerically, the first term is twice the percentage reacting value of calcium and magnesium from analytical data in which the percentage base is the sum of all dissolved constituents, both bases and acids. The first term can be read directly from the numerical scales on the diamond-shaped field of the diagram, in accord with Figure 2-A. Likewise, the second term of the symbol is twice the percentage reacting value of carbonate and bicarbonate, or is scaled directly from the diagram. This form of symbol has the distinct advantage of indicating the general character of a water specifically, without the disadvantage of implying that two waters have distinctly different characters merely because their analyses plot on either side of a boundary between arbitrary subdivisions of any water-analysis diagram. For treatment in a text, waters can be grouped according to limiting values for the two terms of the symbol here proposed, and those limits can be varied at will to suit the discussion of the problem at hand.

This decimal-fraction symbol indicates numerous characteristics of a water simply but specifically. Thus, the more common type of natural water contains chiefly calcium, magnesium, and bicarbonate; its symbol approaches 100.100 as a limit. For its fairly common opposite, the alkali-carbonate water, the symbol approaches 0.100 as a limit. The first term of the symbol indicates relative hardness in percentage of total equivalents. If the second term exceeds the first, all the

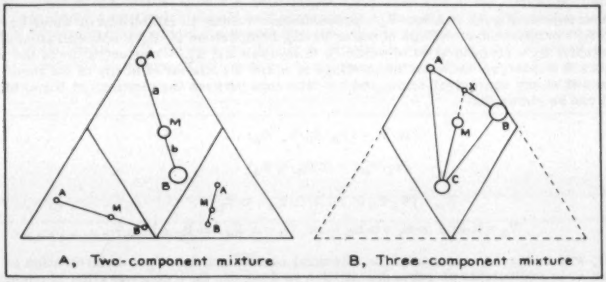


Fig. 5--Preliminary confirmation of mixtures

hardness is carbonate or "temporary" hardness. However, if the second term is smaller, some of the hardness is non-carbonate or "permanent" and the relative amount of non-carbonate hardness is indicated by the numerical difference between the two terms. The first term of the symbol is the percentage complement of the "per cent sodium" introduced by SCOFIELD [5] to measure the effect of a water on the physical properties of a soil when applied for irrigation. Thus, if this term is greater than about 50 the physical condition of the soil is not likely to be impaired seriously, but if the term is less than about 40 such impairment may result.

Mixtures of waters

Many hydrologic problems involve apparent mixtures of natural waters, which the investigator seeks to confirm or disprove. The solution of such problems is facilitated by use of the diagram as described beyond; this use has been anticipated in the initial paper by HILL and in the paper by LANGELIER and LUDWIG, which have been cited.

Mixtures of two waters in all proportions, if all products remain in solution, plot in the three fields on the respective straight lines that join the points representing the respective chemical characters of the two waters mixed. Thus, in Figure 5-A the straight lines AB will include the plottings of every possible mixture of two waters whose chemical characters are represented by points A and B, respectively. Point M represents a possible mixture in one particular proportion.

There is an obvious application of this procedure in demonstrating a cause for deterioration of water quality in a coastal area--whether or not due to simple invasion by ocean water. If so, chemical analyses of the progressively deteriorated water must, within reasonable limits of error, plot on a set of three vectors directed toward the composition of ocean water. If the analyses do

not so plot, simple admixture of sea-water is not a valid and adequate explanation of the deteriorations. For example, on Figure 1 there are plotted the chemical characters of five natural waters from a long shore-area in whose ground-waters, at certain places, the content of chloride and certain other constituents has changed very substantially in recent years. The five waters include: Two from well A, in 1931 and 1940, respectively; two from adjacent well B, in 1931 and 1936, respectively; and one from the ocean a few miles away. From the plottings on Figure 1 it is obvious that this deterioration in ground-water quality could not have been caused by a simple intermingling of the fresh ground-water with ocean water.

To demonstrate conclusively that a certain water is a quantitative mixture of two other waters--neither diluted, concentrated, nor chemically modified after the mixing--one graphic criterion and one graphic-algebraic criterion must be satisfied. First, by the graphic criterion, in all three fields of the diagram the apparent mixture must plot on straight lines between the plottings of its two inferred components. Also, the area-concentration plottings in the central field must conform to the principle that the concentration of a mixture is necessarily greater than the least, but less than the greatest, of the several concentrations of its components. This graphic criterion alone is not decisive because it involves only percentage reacting values and does not involve absolute concentrations. Neither is any other simple graphic construction on the diagram decisive. The second and decisive criterion requires satisfaction of the following equations:

With reference to Figure 5-A let: V_a = proportionate volume in mixture M of water having composition A; V_b = proportionate volume of water having composition B; E_a = concentration of water A, in equivalents; E_b = concentration of water B, in equivalents; E_m = concentration of the mixture, in equivalents; a = intercept between the plottings of A and M, measured in any of the three fields of the diagram and at any convenient scale; and b = intercept between the plottings of B and M. Then it follows and can be shown that

$$(a/b) = (V_b \cdot E_b / V_a \cdot E_a) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

$$(V_a/V_b) = (b \cdot E_b / a \cdot E_a) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

$$E_m = [E_a \cdot E_b (a + b)]/(a \cdot E_a + b \cdot E_b) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

$$V_a = b \cdot E_b / (a \cdot E_a + b \cdot E_b) \text{ and } V_b = a \cdot E_a / (a \cdot E_a + b \cdot E_b) \quad \ldots\ldots\ldots\ldots\ldots\ldots (4)$$

Further, with respect to any particular chemical constituent, let: C_a = concentration in component water A, in equivalents or parts per million as desired; C_b = concentration in component B; and C_m = concentration in the mixture. Then

$$C_m = (C_a \cdot V_a) + (C_b \cdot V_b) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

Decisive proof of a quantitative mixture is accomplished when, for the water of intermediate composition, agreement is shown between analytical data and corresponding values computed from equation (3) for total concentration and from equations (4) and (5) for concentration of individual chemical constituents. Equation (3) is numerically equivalent to a corresponding equation derived by LANGELIER and LUDWIG [2, pp. 350-351], but is expressed in a form that facilitates the necessary computations.

As has been pointed out by HILL [1 (1940), pp. 48-49], the chemical character of a mixture of waters will plot at the center of gravity of the plottings of the respective components, each having been weighted according to its concentration and its proportionate volume in the mixture. Based on this principle, graphic-algebraic criteria for decisive proof of quantitative mixtures are perhaps feasible for a three-component system but become involved for systems with more than three components. Problems involving three or more components are likely to be infrequent; accordingly, it seems most practicable to solve them by an adaptation of the two-component criteria given above. Thus, on Figure 5-B let M represent a water presumed to be a mixture of waters A, B, and C. To prove or disprove a quantitative mixture project a straight line on the diagram through C and M to intersect AB at point X, which represents the chemical composition of a hypothetical mixture of waters A and B in the same proportions that these waters would enter a mixture of composition M. From preceding equations (3), (4), and (5) determine the composition and concentration of water X. Then, treat water M as a presumed mixture of waters X and C. As desired, this procedure is readily adaptable to mixtures of more than three components.

Application to geochemical problems

The greatest utility of the diagram herein described probably is in "screening" a large number of water-analyses for critical study with respect to sources of the dissolved constituents, modifications in chemical character as a water passes through an area, and related geochemical problems.

Changes in the chemical character of a natural water by solution of progressively increasing amounts of some particular mineral must plot on a set of straight-line vectors directed in each of the three fields toward the point representing the chemical composition of the mineral. This case is analogous to mixing one water with another whose concentration is infinitely great.

A natural water may be concentrated progressively by evaporation until it becomes saturated with respect to certain constituents, which then separate out in the solid phase. Until a saturation-point is reached, the chemical character of the concentrating water is represented by a single fixed point in each of the three fields of the diagram. If the material separating in the solid phase is of constant composition then, as evaporation continues, the character of the water will be traced on the respective fields by straight-line vectors directed away from the points that represent the composition of the separating solid. If the solid phase is a simple compound of one cation and one anion, the vector in the central field will be directed away from one of the apexes of that field, each of which represents a particular simple salt or group of salts. In the two triangular fields, the vector will be directed away from the respective apexes that represent the cation and anion composing the solid phase. For example, on Figure 6-A point A represents the composition of a hypothetical water that is saturated with respect to calcium sulphate ($CaSO_4$). As evaporation then

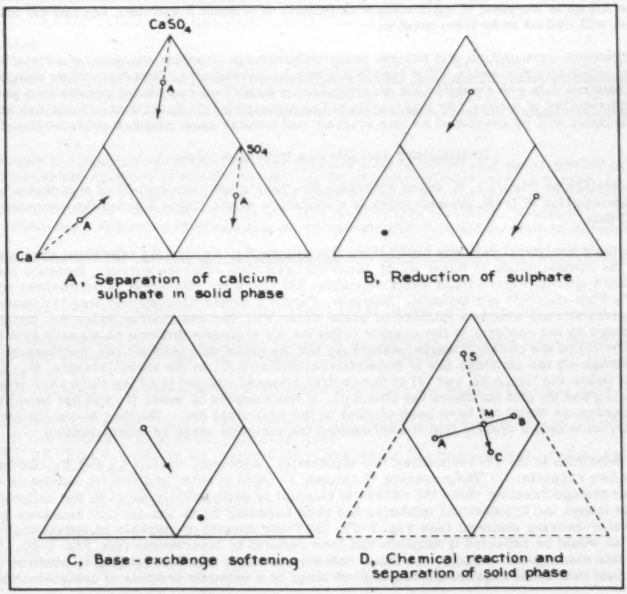


Fig. 6--Vectors characteristic of certain geochemical processes

continues and calcium sulphate forms in solid phase, the changing composition of the liquid phase will trace the three vectors shown. If a separating solid phase is a mixture of salts in a constant proportion, a straight line will be traced in the central field trending away from the point that corresponds to the constant composition of the mixture; straight lines may or may not be traced in the two triangular fields.

Certain changes in the chemical character of a water are caused by chemical reactions which in effect substitute one cation or one anion for another, molecule for molecule. Thus, reduction of sulphate [6] is equivalent to substitution of bicarbonate (HCO_3) for an equivalent amount of sulphate (SO_4); natural softening by reacting with base-exchange minerals [7], to substitution of sodium and potassium (Na, K) for calcium and magnesium (Ca, Mg). These two chemical changes are traced on the diagram by straight-line vectors parallel to the bases of the central field as shown by Figures 6-B and 6-C, respectively.

If two waters (or a water and a mineral) react chemically when brought together and some product or products of the reaction form in solid phase, the chemical character of the products remaining in solution will not plot on the straight line joining the points that represent the two reacting waters. Rather, it will plot on the extension of the straight line drawn from (1) the point that represents the composition of the solid phase to (2) the point that indicates the proportionate volumes and compositions of the two reacting waters. Thus, in Figure 6-D suppose that waters A and B are brought together in a proportion indicated by point M on the straight line AB, and that a solid phase of composition S results; then, the soluble products will plot on the extension of the straight line SM, as at point C. If the precipitate is a compound of one base and one acid, this relation between points A, B, M, S, and C will apply likewise in the two triangular fields (not shown) and point S will fall on one apex of each field. If the two waters are brought together in various proportions and the product S is appreciably soluble, the composition of the liquid phase will traverse line AB up to the point of saturation with respect to product S and then, beyond the point of saturation, will deflect away from point S.

The chemical composition of a natural water may undergo complex changes by an interplay of several or numerous processes. The causes are commonly obscure. However, when comprehensive chemical data are available the diagram herein described can assist greatly in a preliminary discrimination of causes, by application of the principles just described. Doubtless other useful principles will be developed as this diagram and similar diagrams are more widely used.

Preliminary analysis of a typical problem

The plottings on Figure 1, to which reference has been made, are typical of a problem in the saline contamination of fresh ground-water in a longshore area. Table 2 gives the corresponding numerical data.

From their analytical data one could infer that waters B_1, A_2, and B_2 represent progressive stages in the contamination of water A_1 by some unknown high-chloride source. Because these are longshore ground-waters from wells only about 200 feet deep, the ocean is an obvious potential source of a high-chloride contaminant. However, Figure 1 shows conclusively that the contaminated ground-waters are not simply a mixture of ocean water with uncontaminated water A_1, because their plottings do not conform to the graphic criterion for a simple mixture as already developed. Specifically: (1) In the cation-triangle, waters A_2 and B_2 do not fall between the plottings of A_1 and C, although all the plottings are in substantial alignment; (2) in the anion-triangle, B_1, A_2, and B_2 all plot below the line A_1C; and (3) in the central diamond-shaped field B_1 plots very slightly above, but A_2 and B_2 plot far above the line A_1C. If the analysis of water B_2 had not been available, these discordances would not have been obvious in the analytical data. Neither would the analysis of water B_1 have shown clearly that it represented the incipient stage of contamination.

With reference to the corresponding two hypothetical mixtures, waters A_2 and B_2 contrast sharply in two respects: (1) Their content of calcium is much greater and that of sodium is much less; in percentage reacting value the excess of calcium is substantially equal to the deficiency of sodium, as though the hypothetical mixtures had been hardened by an ion-for-ion exchange of bases with the water-bearing material (see Fig. 6-C). (2) Their content of sulphate is substantially deficient, as would be expected if sulphate had been reduced to bicarbonate (see Fig. 6-B). These two contrasts also appear to apply in a small measure to water B_1, thus tending to confirm the inference that this water represents an incipient stage in a common process of contamination.

Table 2--Principal chemical constituents of certain longshore ground-waters and of ocean water

Constituent	A_1	B_1	b_1	A_2	a_2	B_2	b_2	C
Parts per million								
Calcium (Ca)	39	40	39	102	42	466	65	393
Magnesium (Mg)	10	10	11	19	22	77	98	1,228
Sodium (Na)	47	52	56	54	152	255	808	10,220[a]
Potassium (K)				3.6				353
Carbonate (CO_3)	....	....	....	0	....	....	....	0
Bicarbonate (HCO_3)	204	207	204	203	203	166	199	139
Sulphate (SO_4)	24	21	26	6.7	49	0	207	2,560
Chloride (Cl)	16	32	32	199	199	1,346	1,346	18,360
Percentage reacting values (adjusted)								
Calcium (Ca)	20.2	19.6	18.4	28.0	10.0	28.6	3.5	1.7
Magnesium (Mg)	8.5	8.1	8.6	8.6	8.6	7.8	8.7	8.8
Sodium and potassium (Na + K)	21.3	22.3	23.0	13.4	31.4	13.6	37.8	39.5
Totals	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0
Bicarbonate (HCO_3)	38.9	35.9	34.9	18.3	16.7	3.3	3.6	0.2
Sulphate (SO_4)	5.8	4.6	5.7	0.8	5.1	0	4.7	4.6
Chloride (Cl)	5.3	9.5	9.4	30.9	28.2	46.7	41.7	45.2
Totals	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0

[a]Calculated.

Notes: A_1 and A_2 indicate water from Well A on June 3, 1931, and December 20, 1940, respectively. B_1 and B_2 indicate water from Well B on June 6, 1931, and June 30, 1936, respectively. C indicates water from the ocean a few miles from wells A and B. a_2, b_1, and b_2 indicate hypothetical mixtures of waters A_1 and C in such proportions that their chloride contents are equal to those of A_2, B_1, and B_2, respectively.

Obviously the data here presented are not adequate fully to define this water-quality problem, in part because the analyses of waters A_1, B_1, and B_2 are approximate only. However, as an elementary example of procedure they are especially effective because they afford a striking comparison but involve only water-quality and time as principal variables. A complete solution of the problem here suggested involves data so voluminous that it is not feasible to introduce them.

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[2] W. F. LANGELIER and H. F. LUDWIG, Graphical methods for indicating the mineral character of natural waters, J. Amer. W. W. Assn., v. 34, pp. 335-352, 1942.

[3] Op. cit., Fig. 5.

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DISCUSSION

RAYMOND A. HILL (Consulting Engineer, Los Angeles, California)--When the use of trilinear diagrams in the interpretation of water-analyses was suggested by the writer (R. A. HILL) at a meeting of the Section of Hydrology, American Geophysical Union, it was not expected that so many variations in the form of the diagram would be developed by others. In fact, as stated by the writer in his paper on Salts in irrigation water [Trans. Amer. Soc. Civ. Eng., v. 107, 1942], it has been a matter of regret that so much effort has been directed toward modification of the diagram rather than toward its application as a tool in solving hydrological problems. However, such being the case, it is probable that the most desirable form of diagram has not yet been developed.

The form of diagram used by the author (PIPER) is essentially the same as that suggested by the writer in Figure 12 of his closing discussion of the above mentioned paper. This form tends to be somewhat confusing in actual application because there is no marked differentiation between the three component parts of the diagram, that is, the cation-triangle, the anion-triangle, and the geochemical diamond. Since all graphical projections from either of the triangles to the diamond are along diagonal lines, the triangles can be separated from the diamond as shown in Figure 1, on which, for illustration, have been plotted the points corresponding to the analysis of sample A_1 in Table 2 of Mr. PIPER'S paper as follows:

	pct		pct		pct
Ca	40.4	HCO_3	77.8	Primary alkalinity	20.4
Mg	17.0	SO_4	11.6	Primary salinity	22.2
Na + K	42.6	Cl	10.6	Secondary alkalinity	57.4
	100.0		100.0		100.0

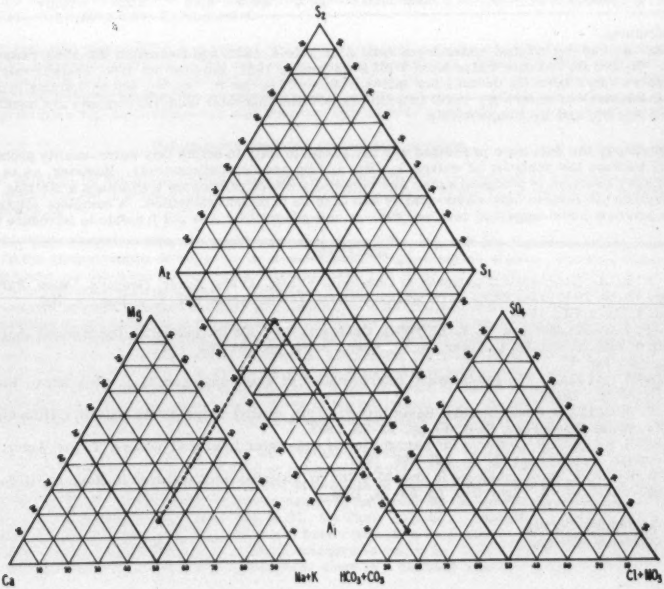


Fig. 1--Illustrative plotting of Sample A, Table 2

While the use of circles of different areas to indicate relative concentrations was suggested by the writer in his paper (Op. cit.) it is doubtful whether this is of value in many cases. Better visual representations of differences in concentration can be had by the use of bar-diagrams.

The reversion by the author to the practice of computing percentage reacting values so that the sub-total of the cations and of the anions each equals 50 per cent seems to introduce unnecessary confusion. Furthermore, as the cations are positive and the anions are negative their sum is properly equal to zero. If the equivalent weight of each cation be recorded as a percentage of the equivalent weight of all cations, and the same be done for the anions, then it would be unnecessary to double the percentage reacting values as described by the author throughout his paper.

The use of the reciprocal of the combining weight of each ion also tends to be confusing. Almost everyone conversant with such matters remembers the combining weights of the more common ions, while it is not to be expected that the reciprocals can be remembered. The only advantage in using reciprocals would be ease of multiplication as compared to division. The data, however, are subject to far greater error than are ordinary slide-rule computations and division on a slide-rule is as simple as multiplication.

In his discussions of mixtures of waters the author resorts to algebraic computations which become involved in actual use. It was for this reason that the writer in his paper (Op. cit., pp. 1,484) suggested the use of tons-equivalent, abbreviated to "T_e", being the equivalent tons of hydrogen in the quantity of water under consideration. When this quantity is given in acre-feet the total equivalent weight of any ion is equal to the quantity of water times the concentration in milligram-equivalents of hydrogen per liter divided by 735, or algebraically, $T_e = (CQ/735)$, in which C is the concentration of salts in equivalents per million and Q is the quantity of water in acre-feet. The factor 735 comes directly from the use of acre-feet and tons as units. Any corresponding factor would likewise come directly from any other system of measurements.

None of the systems of classification of different waters dependent on reference to the plotted position of a point on a diagram can be remembered readily and hence all such fail of being descriptive. It was for that reason that the writer suggested in his closing discussion of his paper on Salts in irrigation water that the most satisfactory classification would be one that merely defined the predominate cation and the predominate anion.

In closing, attention is invited to the fact that any trilinear diagram adapted to the interpretation of water-analyses is only a tool; hence the form of the tool should be subordinated to the use which is made of it.

W. F. LANGELIER (Professor of Sanitary Engineering, University of California, Berkeley, California)--In a recent paper to which the author has made reference [his reference 1], LANGELIER and LUDWIG described several methods of graphing water-analyses and suggested possible applications thereof. Among the methods described is one to which we referred as our own adaptation of the trilinear method of R. A. HILL [Salts in irrigation water, Proc. Amer. Soc. Civ. Eng., v. 67, p. 975, 1941]. This method, it appears, is substantially the same as that proposed in the paper under discussion. Our adaptation of the HILL method consisted merely in changing the outward form of the diagram so as to permit the use of standard triangular graph-paper. We wish to disclaim any originality in developing the basic trilinear method. To us, this three-point method seems to be unnecessarily cumbersome in execution and, in the graphs, difficult of visual interpretation; moreover, we believe that the multiple graph is not well suited to the study of any considerable number of dissimilar analyses upon a single diagram.

In the multiple trilinear form of graph as proposed, each analysis is regarded as comprising six component-ions, or ion-groups, which require three points upon the diagram for complete identification and interpretation. For most uses, it would appear that a more practicable method is one in which the general character of the sample is indicated by the position of a single point, and wherein more specific or critical data are indicated by special characters or symbols. We have described such a method and, in order to distinguish it from the one at present under consideration, have referred to it as the "single-point" method. In the single-point method, the cations and anions are divided into chemically similar groups, essentially as proposed by PALMER, that is, the cations are divided into alkali-groups and non-alkali groups, and the anions are divided into carbonate and non-carbonate groups. Since the total equivalent concentrations of the cations and anions are equal, and since there are only two groups in each category, it follows that there will be only two independent variables and that therefore the analysis can be represented by a single point upon a rectangular graph. The significance of the plotted point in this diagram is identical to that of the third point

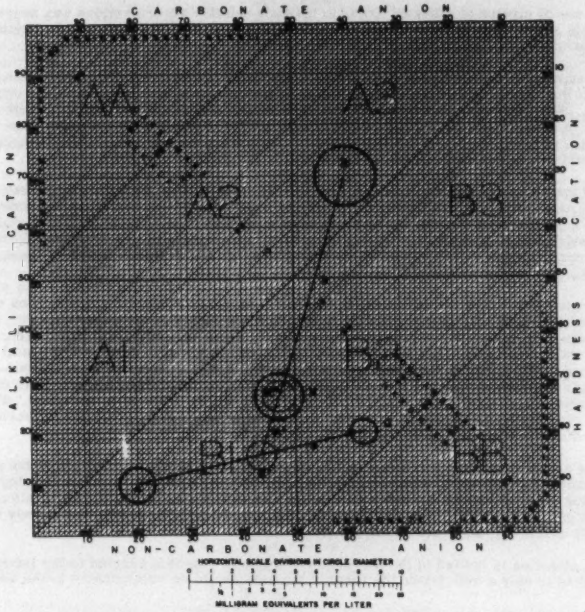


Fig. 1--Use of water-classification diagram in confirming a presumptive mixture of three component waters [After Langelier and Ludwig (J. Amer. Water-Works Ass'n., v. 34, pp. 335-352, 1942)]

(obtained by projection) in the multiple trilinear graph. It should be noted that in either diagram the position of the identifying point--which actually classifies the sample--is not altered by changes in the ratio of either Ca to Mg or Cl to SO_4.

As an illustration of the use of the rectangular graph as applied to the problem of mixtures, reference is made to Figure 1, in which circle A in the triangle B1 represents a water of which the total cation-concentration is 12.0 milligram equivalents per liter (mE/ℓ). Its plotted location indicates that it contains 1.2 mE/ℓ of alkali cation and 2.4 mE/ℓ of chloride plus sulphate anions. The fact that its position lies below the SW-NE diagonal indicates that the non-carbonate anion-content of this water is greater than its alkali content and, in accordance with PALMER, the water may be said to be characterized by the property of secondary salinity or non-carbonate hardness. The three properties--non-carbonate alkali, non-carbonate hardness, and carbonate hardness--can be read directly from the inside scales as 10, 10, and 80 per cent of the total salt-concentration, equal to 1.2, 1.2, and 9.6 mE/ℓ, respectively. Similarly, the properties of water samples B, C, and M are apparent from their plotted positions.

The significance of the six outer lettered triangles of the diagram is that each delimits a property which, measured in percent, is greater than the other two combined. Within the inner triangles, A2 and B2, the three properties are more evenly balanced, and none exceeds 50 per cent of the total.

Sample M falls within the triangle formed by the plotted positions of A, B, and C, and its total concentration of dissolved salts is greater than the lowest and less than the highest of the three

waters. This is presumptive evidence that the sample might possibly constitute a mixture of the three samples, A, B, and C. That it is not an exclusive mixture of any two of the three samples is readily proved by mere inspection of the diagram. It has been repeatedly pointed out that a basic principle of these graphic methods is that the plotted location of a mixture of any two waters must lie on the line which connects the plotted positions of the two component parts and that the proportion of each component in the mixture is related to the exact position of the point upon the connecting line. Thus in Figure 1, sample M cannot be an exclusive mixture of any two of the three samples represented, because its plotted position does not coincide with the lines interconnecting any two of the samples. However, it might possibly be a mixture of all three samples. The proof that M is not a quantitative mixture of all three samples takes into further consideration the total concentration of the sample as indicated by the diameter of the circle. If M were an exclusive mixture of A, B, and C, it could be considered to be a two component mixture of B and a hypothetical mixture M', the latter composed of waters A and C. As indicated by the author, we demonstrated in our earlier contribution, the relationship which must be satisfied between ΣM, the total concentration of M', and the analytical values of Σ_A, Σ_C, and the scaled distances of a and c. The formulation is

$$\Sigma_{M'} = \Sigma_A[1 + (a/c)]/[1 + (\Sigma_A/\Sigma_C)(a/c)]$$

In the example under consideration the computed value of $\Sigma_{M'}$ will be found to equal 7.8 mE/ℓ. Applying the same formulation, Σ_M, if it were a mixture of B and M', would equal 9.3 mE/ℓ. Since this computed value differs from its actual or analytical value of 20.0 mE/ℓ, sample M cannot be an exclusive mixture of A, B, and C.

In addition to the above method of confirming mixtures, we have described a completely graphical method which, however, requires that the analytical data be rearranged into six groups rather than four. For this purpose and for other uses wherein a considerable number of analyses are represented we recommend large graph sheets approximately 18 inches square.

We concur in the author's opinion that there exists a wide and practically untried field of usefulness in the application of graphical methods to geochemical water-supply investigations.

ARTHUR M. PIPER (author's reply and closure)--In his lead paper on the general topic of graphic methods in geochemical studies the writer sought to define his own procedure in order that its elements might be compared with those of procedures outlined by HILL and by LANGELIER in their respective antecedent papers, and thereby possibly to stimulate the evolution of some technique even more effective. He had no thought of claiming originality for all elements in his procedure as outlined. That procedure is founded on a multiple-trilinear diagram which was developed by the writer independently, but which fortuitously had evolved to essentially its present form about contemporaneously with the papers by HILL and by LANGELIER in 1942. However, the writer here acknowledges with embarrassment that he had been confused by the dual publication under the title of "Salts in irrigation water" [R. A. HILL, Proc. Amer. Soc. Civ. Eng., v. 67, pp. 975-990, 1941; also idem, v. 68, pp. 1,478-1,493, 1942] and heretofore has overlooked not only the discussions by SCOFIELD and others but also HILL'S "alternate form of geochemical chart" [op. cit. pp. 1,494-1,518, Fig. 12, 1942], which is essentially identical with the water-analysis diagram of the lead paper.

The diagram of the lead paper is conceived by the writer as a technician's tool which--for the particular purpose of segregating related chemical analyses from a mass of such data in the study of a geochemical problem--has substantial advantages over either a set of bar-diagrams or a rectilinear graph, and which seems not to sacrifice any great advantage. Its over-all utility is afforded by the use of trilinear coordinates to indicate the chemical character of a water by single-point plotting for preliminary segregation of data and by three-point plotting for more critical segregation. It is conceded that such coordinates may seem awkward to the novice but that awkwardness passes quickly as familiarity with the diagram is acquired.

The central or diamond-shaped field in the diagram of the lead paper is essentially a counterpart of the LANGELIER "water-classification diagram", except that its coordinates are triangular rather than rectilinear. On that central field, single-point plottings for preliminary segregation of data are made and the characters of waters are disclosed precisely as on the LANGELIER diagram. With either diagram, this single-point plotting treats the sum of calcium and magnesium as a single variable, and the sum of sulphate and chloride as another single variable. Within this restrictive treatment the rectilinear LANGELIER diagram is entirely adequate and probably simpler than the central field in the diagram of the lead paper; however, for a more critical segregation of data this restrictive treatment is not adequate because it does not treat all six "first-rank" constituents as

independent variables. On the diagram of the lead paper all six are treated independently by means of the three-point plotting, which is feasible only with triangular coordinates.

Fundamentally, the HILL "geochemical chart" differs from the diagram of the lead paper only in that it treats chloride and sulphate-plus-bicarbonate as complementary anion-constituents, rather than chloride-plus-sulphate and bicarbonate. In the writer's judgment the grouping of sulphate with bicarbonate on the HILL chart would confuse rather than clarify many geochemical problems and does not seem peculiarly adapted to problems of irrigation-waters.

With respect to the demonstration of a quantitative mixture of two waters, one fundamental point seems not to have been made sufficiently clear--that is, not only must the three-point plottings on the diagram of the lead paper or on the HILL "geochemical chart" define three straight lines in the several plotting fields but also the analytical data must conform to equation (3) of the lead paper, or to the equivalent of that equation. This two-element demonstration is adequate only with respect to the six "first-rank" constituents. With respect to any one "second-rank" constituent, a quantitative mixture is demonstrated only when equations (4) and (5) of the lead paper also are satisfied. With only one-point plottings on either of these two diagrams or on the LANGELIER diagram, a quantitative mixture is demonstrated only when a straight line is defined on the diagram and equations (3), (4), and (5) of the lead paper (or equivalents of those three equations) are satisfied with respect to both first-rank and second-rank constituents. The three-point plottings are much more quickly made than the additional computations required with single-point plottings.

In his discussion of the lead paper HILL implies that equations (3), (4), and (5) are needlessly involved. In this connection it seems unnecessary to point out that these equations express the inescapable basic principles in simple form, also that the concept of "tons-equivalent" merely introduces an additional conversion-factor.

Although graphic methods are very useful in discriminating two-component mixtures, it is felt that their primary utility lies in tracing chemical reactions between a natural water and materials with which that water comes in contact. The lead paper describes several principles that are applicable in such studies and perhaps creates a background for delineating other useful principles and for evolving an ultimate comprehensive technique.

CORRELATION OF GROUND-WATER LEVELS AND PRECIPITATION ON LONG ISLAND, NEW YORK

C. E. Jacob

(Published with the approval of the Director, U. S. Geological Survey)

PART II--CORRELATION OF DATA

A brief though concise statement of the history of ground-water studies on Long Island, beginning with the early water-level observations in Brooklyn by STODDARD in 1854, was given by THOMPSON [see 7 of "References" at end of paper]. These and other early data were considered later by LEGGETTE [8]. He evaluated them by means of a graph of the cumulative departure of precipitation. More recent studies by LEGGETTE [9] and by the writer have lead to the procedure outlined in Part I of this paper [10], which was founded upon an empirical approach suggested by LEGGETTE and was later justified by analysis based on the theory of BOUSSINESQ [11].

Figure 1 is a map of the central part of Long Island showing contours on the water-table as of May, 1943, and also the locations of 14 New York City test-wells upon whose records the present study is based. The contours are based upon data from many more wells than are actually shown on the map. The 14 wells whose water-levels are analyzed in this study were first measured by the Department of Water Supply, Gas, and Electricity of the City of New York. They were chosen because of the length and continuity of their records and because together they adequately cover the range of water-table elevations in the area with more or less uniform distribution. Other wells with records of equal or greater length were eliminated because of less favorable situation with respect to centers of pumpage, points of natural discharge, etc., or because they duplicated records of one of the 14 wells.

Section A-A' in Figure 1 shows the configuration of the ground-surface and of the water-table on what may be considered a typical section of the area under consideration. The hills along the north shore of the island are composed of glacial drift. At about the maximum elevation, running roughly parallel to the length of the island, are morainal deposits that represent the farthest southward advance of the ice during successive glacial stages. South of the terminal moraine is a gently sloping outwash-plain of somewhat permeable material. These glacial deposits of varying thickness were laid down on a land-mass having roughly the form of the present island, composed of Cretaceous sediments. Beds of supposed Magothy age, the uppermost Cretaceous strata in the area, are composed of interbedded sands and silts several hundred feet in thickness. Underlying these are beds of clay assigned to the Raritan formation of the Upper Cretaceous series, and the Lloyd sand, also considered to be part of the Raritan, which rests unconformably upon the basement-rock or its weathered equivalent.

The north shore of the island is cut by numerous bays and by small but steep streams, some of them fed by springs. The streams flowing into the bays on the south shore have gradual slopes and are fed by the main ground-water table. They modify the shape of the water-table, as seen in Figure 1. North of the terminal moraine perched water-tables are produced by relatively impermeable beds above the main ground-water table. These also modify the main water-table, reducing its curvature. The asymmetry of the water-table profile shown in Section A-A' may be attributed, then, partly to the above causes and also partly to the variations in permeability and thickness of the more permeable intercommunicating beds.

Figure 2 gives in graphical form the water-level records of the 14 wells, expressed in terms of elevation above mean sea-level. During the earlier years water-level readings were made frequently in some of these wells though not at regular intervals. Unfortunately no readings were taken from 1919 to 1931. From 1932 to 1935 readings were rather intermittent. The continuing program of regular observations of water-levels on Long Island was begun in the summer of 1936. Eight of the 14 wells have continuous month-by-month records from that time to the present. These eight wells are indicated by an asterisk in Table 1, which gives pertinent data on all 14 wells.

Table 1--Data regarding 14 shallow test-wells in Nassau and Suffolk counties, New York

Well	Locality	Ratio 14-well average to elevation water-level in well (1914, 1937-42) (C) [a]	Approximate depth to water 1942	Elevation mean water-level for 1942 (Sandy Hook datum)
			ft	ft
N 1616	Westbury	0.5816	43	79.64
*N 1256	Old Westbury	0.6143	37	75.28*
N 1614	Garden City Park	0.6925	34	67.18
*N 1255	Garden City	0.7701	19	60.12*
*S 1806	Pinelawn	0.8383	32	54.82*
N 1259	Plainedge	0.9066	28	50.86
*S 1810	Brentwood	0.9201	40	49.76*
*N 1263	Jerusalem	0.9350	17	49.19*
N 1615	East Hempstead	1.072	19	43.77
S 1805	Maywood	1.110	16	41.40
*S 1809	near Bayshore	1.660	13	28.15*
*S 1807	near Babylon	2.175	3	21.71*
*S 1803	near Babylon	2.937	6	16.17*
S 1808	near Bayshore	4.392	5	10.95
Average for all 14 wells			22	46.36
Average for the eight wells marked * upon which are based monthly composite averages for 1936-41				44.40
Ratio of the above averages				1.044

[a] C = Average of the ratios (for the years 1914 and 1937 to 1942) of (average altitude of mean annual water-levels in 14 wells) to (altitude of mean annual water-level in the given well).

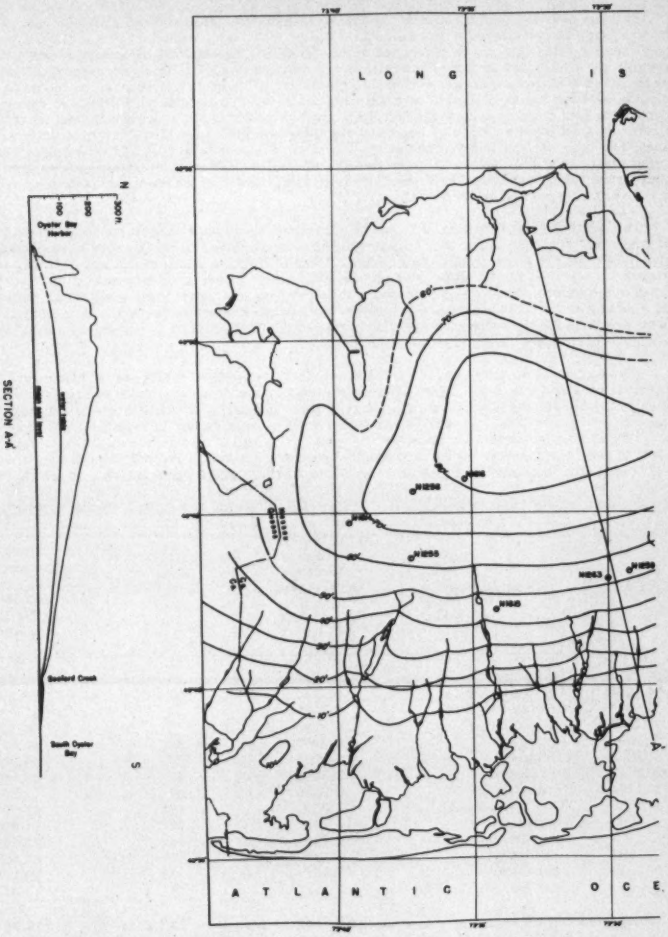
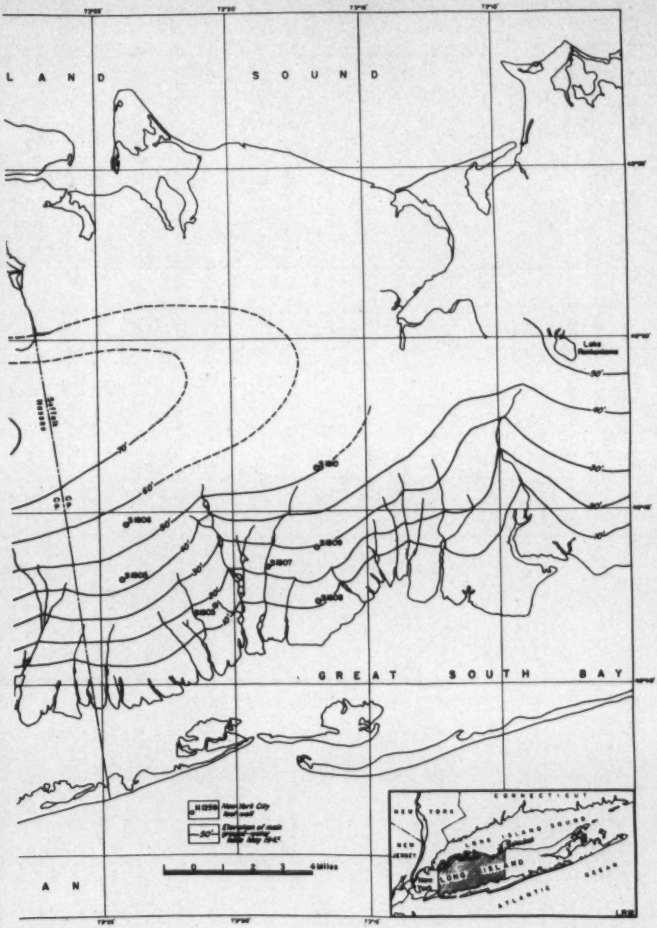
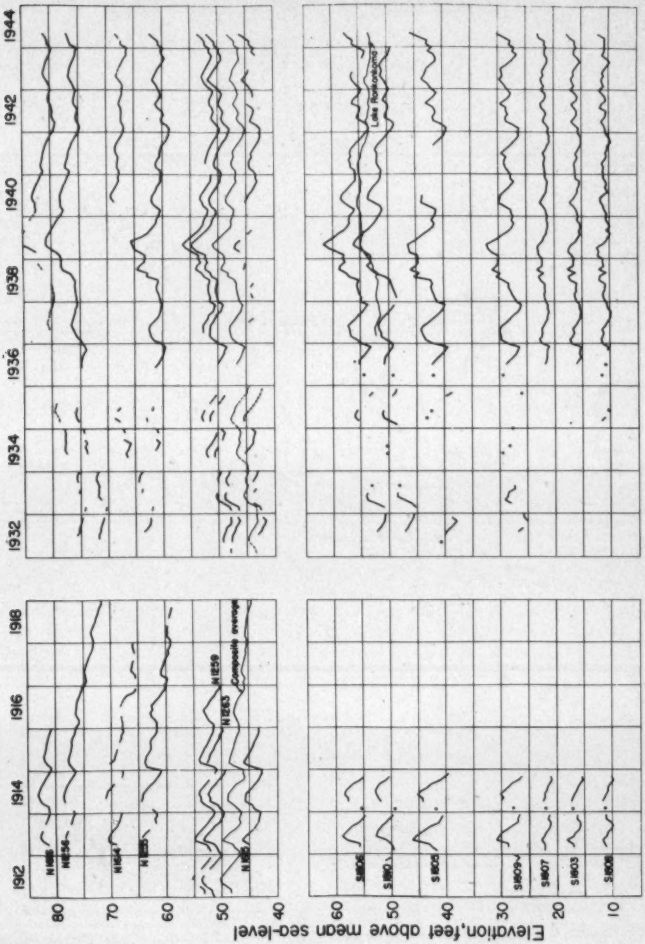


Fig. 1--Map of Nassau County and western Suffolk County, Long Island, New York, showing



configuration of main ground-water table in May, 1943, and location of shallow test-wells


Elevation, feet above mean sea-level
80
70
60
50
40
60
50
40
30
20
10
1912
1914
1916
1918
1932
1934
1936
1938
1940
1942
1944
N1855
N1854
N1847
N1835
N1852
N1859
N1863
Composite average
S1806
S1807
S1805
S1809
S1807
S1803
S1808
Lake Richardson

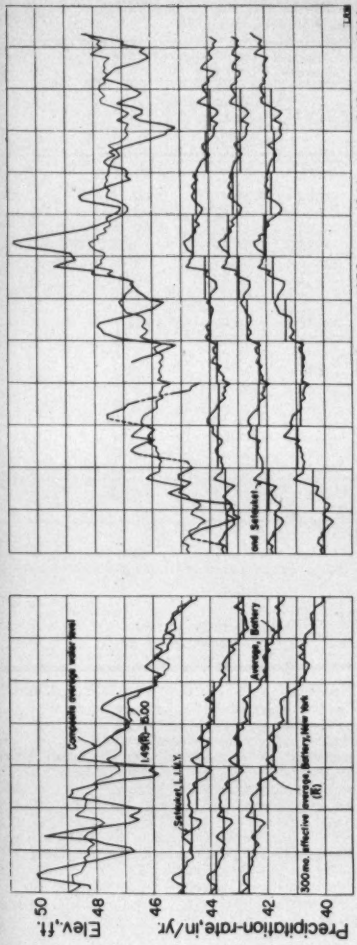


Fig. 2--Month-by-month record of water levels in 14 shallow test-wells on central Long Island for 1912-18 and 1932-44, compared with effective average rate of precipitation

As shown by the last two columns of Table 1, the approximate depth to water in the wells is on the average about half the elevation of the water-surface in the same wells though there is considerable variation from well to well. Although the depth of the water-table below the ground-surface may be a determining factor in the relation between rainfall and changes in ground-water level during and following individual storms, it has much less bearing upon long-term or secular variations of water-level such as are considered in this study.

The principal centers of net withdrawal from the shallow water-producing beds in the area under consideration are the infiltration-galleries and shallow-well stations of the City of New York, in the southern part of Nassau County. During the years 1912 to 1918 the average rate of withdrawal from this system was about 38 million gallons per day (mgd), whereas from 1932 to 1941 the average rate of withdrawal was only about 23 mgd. However, the observation-wells on whose records the present study is based are all sufficiently distant from these centers of pumpage that the effect on their water-levels may be neglected.

Table 2 gives "composite average water-levels" and "effective average rates of precipitation" by years for the periods 1912 to 1918 and 1932 to 1941. The yearly values of composite average water-level were computed from annual mean water-levels in 14 or fewer wells. The number of wells for which there is sufficient record to determine an annual mean water-level for a given year is found in the third column of Table 2. For the years 1914 and 1937 to 1942, measurements were frequent enough and were so distributed that annual mean water-levels could be obtained for all 14 wells. For anyone of those years the composite average water-level is merely the average of the 14 values of mean annual water-level. The composite average water-level for anyone of the other years was determined by comparing the average water-level in the wells for which records are available for that given year with the average water-level in the same wells during 1914 and 1937 to 1942. That is to say, if the number of

Table 2--Comparison between composite average water-level and effective average rate of precipitation on Long Island, New York

Year	Elevation composite av. water-level, $\bar{h}$	No. of wells	Effective average rate of precipitation Battery, New York			
			25-year, $\bar{R}$	Δ[a]	300-month (yearly mean), $\bar{R}'$	Δ'[b]
(1)	(2)	(3)	(4)	(5)	(6)	(7)
	ft		in/yr	in/yr	in/yr	in/yr
1912	48.53	2	42.53	-0.51	42.66	-0.43
1913	47.65	11	42.55	+0.39	42.43	+0.19
1914	47.77	14	41.76	-0.62	42.23	-0.16
1915	47.74	7	41.62	-0.75	41.79	-0.62
1916	46.96	4	40.92	-0.76	41.32	-0.37
1917	45.85	3	40.72	+0.12	40.73	+0.07
1918	45.10	2	40.07	+0.14	40.37	+0.42
1932	43.34	6	40.01	+1.83	40.02	+1.78
1933	44.45	9	40.76	+1.57	40.41	+1.11
1934	45.86	6	41.13	+0.58	40.99	+0.36
1935	46.41	10	40.53	-0.65	40.86	-0.34
1936	46.13	3	40.99	+0.15	40.78	-0.15
1937	46.84	14	41.58	+0.10	41.34	-0.23
1938	47.54	14	42.01	-0.11	41.78	-0.43
1939	48.66	14	41.60	-1.69	42.07	-1.23
1940	47.46	14	41.91	-0.14	41.84	-0.29
1941	46.76	14	41.52	+0.12	41.73	+0.29
Mean	46.65	...	41.31	0.602	41.37	0.498

[a] $\Delta = [(46.65 \text{ ft})\,\bar{R}/(41.31 \text{ in/yr}) - \bar{h}]$. [b] $\Delta' = [(46.65 \text{ ft})\,\bar{R}'/(41.37 \text{ in/yr}) - \bar{h}]$.

wells for which records are available is n, the composite average water-level for a given year is determined by

$$\frac{(\text{avg water-level in all 14 wells for 1914, 1937-42})}{(\text{avg water-level in n wells for 1914, 1937-42})} \times (\text{average water-level in n wells for the given year})$$

Values of composite average water-level were determined also month by month. These values are plotted twice in Figure 2--in the upper blocks of that diagram to the same scale as the water-level data for the several wells, and in the lower blocks of the diagram to five times that scale. The composite average water-level is seen to follow closely the trend of water-level in wells N-1263 and N-1259. It is believed that this "composed" or "composite" average water-level graph would practically duplicate the mean water-level graph of the 14 wells that would have been obtained if all those wells had been measured each month during the period of record. The method by which this continuous though artificial record was composed was as follows:

The monthly composite average water-levels for 1942 are simply arithmetic means. For the years 1936 to 1941 the monthly composite average water-levels were determined by multiplying the corresponding average water-levels for eight of the 14 wells by the constant 1.044. As indicated in Table 1, this constant was determined by taking the ratio of the average for all 14 wells of the mean water-levels for 1942 to the corresponding average for the eight wells. These eight wells are those that have continuous records of monthly readings during the period 1936-41. For the years before 1936 the monthly composite average water-levels were determined by means of the coefficients (C) given in the third column of Table 1, the derivation of which is explained in a footnote to that Table. For example, if at the end of a given month water-level measurements were made in only four wells, the composite average water-level for that month was determined by multiplying the elevation of the water-level in each of the four wells by the appropriate coefficient, summing such products, and dividing the sum by four.

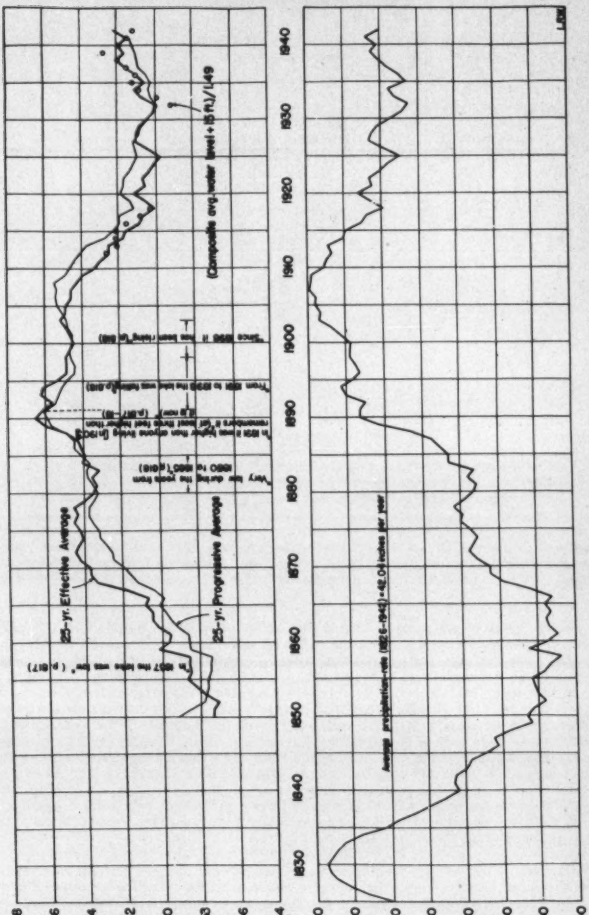


Fig. 3.--Long-term year-by-year record of precipitation at the Battery expressed as cumulative departure and as progressive and "effective" averages, and compared with composite average water-level on central Long Island and with reported levels of Lake Ronkonkoma

Values of the 25-year effective average rate of precipitation plotted in Figure 3 were computed by the method outlined in Table 2 of Part I of this paper [12] from data obtained by the United States Weather Bureau at the Battery in New York, New York. Values for the years 1912 to 1918 and 1932 to 1941 are tabulated in Table 2 (Part II). Also there are tabulated in Column (6) of that Table yearly mean values of the 300-month effective average rate of precipitation for the same years computed

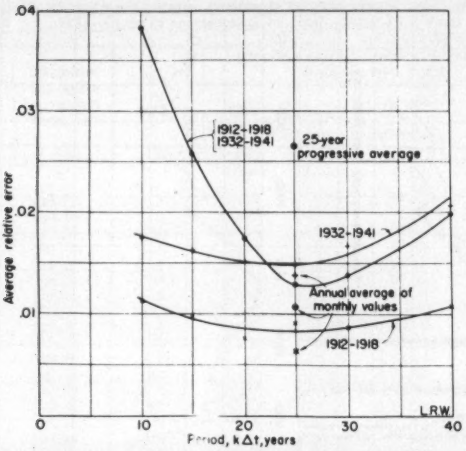


Fig. 4--Graph of average relative error of linear correlation between effective average rates of precipitation at the Battery and composite average water-level on Central Long Island

by the same method. Values of 300-month effective average rate of precipitation, from which these yearly means were determined, are plotted in the lower blocks of Figure 2, not only for the Battery but also for the station at Setauket, Long Island. Also there is given the average for the two stations.

Effective average rates of precipitation were also determined on the basis of 10-, 15-, 20-, 30-, and 40-year periods of adjustment from the same rainfall-data. It was found by trial that the best correlation with the composite average water-level for both periods of record on a yearly basis was obtained with the 25-year effective average. This may be seen from Figure 4, in which are plotted values of average relative error of the correlation against the period of adjustment, $k\Delta t$. The meaning of "average relative error" is illustrated in Table 2. The average elevation of the composite average water-level ($\bar{h}$) for the 17 years of record is 46.65 feet. The average value of the 25-year effective average rate of precipitation ($\bar{R}$) for the same 17 years is 41.31 inches per year. If the basic assumptions of the theory in Part I were met, there should be continuously a direct proportion between $\bar{h}$ and $\bar{R}$ of constant value: (46.65 ft)/(41.31 in/yr). On this basis one may multiply the values of $\bar{R}$ by this ratio and subtract the corresponding values of $\bar{h}$ to obtain the residuals Δ. The average of the absolute values of the residuals is in this case 0.602 foot. Referring this to the average value of $\bar{h}$, the relative value of the average residual, or the "average relative error", is found to be (0.602 ft)/(46.65 ft) = 0.0129.

Actually, correlations were first effected with the water-level records of individual wells of the group of 14. Then, to simplify the work, and in a sense to summarize those correlations, the composite average water-level was adopted. It was found, as was to be expected, that the correlation could be improved further by using instead of the values of 25-year effective average given in Column (4) of Table 2 the yearly means of the 300-month effective average, given in Column (6) of that Table. It should be pointed out that the 25-month effective average and the 300-month effective average involve the same period of adjustment (25 years = 300 months) and that they are based on the same basic data, but that the latter divides the period into 12 times as many intervals. A comparison between the two may be effected by connecting year-end values of the 300-month effective averages plotted in Figure 2 with straight-line segments, as the year-end values of necessity coincide with the corresponding values of the 25-year effective average.

The yearly mean values ($\bar{R}'$) of the 300-month effective average are indicated in Figure 2 by bars extending over each year's record. The average of these for the 17 years of record is shown in Table 2 as 41.37 feet. Multiplying successive values of $\bar{R}'$ by the ratio (46.65 ft)/(41.37 in/yr) = 1.128 ft/(in/yr) and subtracting corresponding values of $\bar{h}$, one gets the residuals Δ', which average 0.498 foot in absolute value. Here, then, the average relative error is 0.0107. This value is plotted on the 25-year line in Figure 4 as a bold open circle in contrast to the light open circle on the same line at 1.29 per cent representing the average relative error of the correlation between the composite average water-level and the 25-year effective average rate of precipitation.

The smooth curve drawn through the points for the correlations based on the 17 years of record (1912 to 1918 and 1932 to 1941) shows a minimum at $k\Delta t$ = 26 years. Similarly the smooth curves for correlations based on the period 1912 to 1918 and on the period 1932 to 1941 both show minima at about 24 or 25 years.

There is plotted in Figure 3, as a light line on the upper block of that diagram, a curve of the 25-year progressive average rate of precipitation. A given point on that curve represents the average rate of precipitation at the Battery for the preceding 25 years. That curve was also correlated with the composite average water-level over the same 17 years of record in the manner described above for the effective average precipitation-rates. The average relative error was found to be 0.0264, as plotted in Figure 4.

Correlations were also effected between the composite average water-level and effective average rates of precipitation at Setauket, Long Island. Inasmuch as the record at this station only goes back to 1886, or only 26 years beyond 1912, it is not possible to compute 30- and 40-year effective averages for the entire period of water-level records. Data for the 10-, 15-, 20-, and 25-year effective averages suggest that the optimum period of adjustment is again about 25 years, with an average relative error of about 0.016.

An effort was made empirically to improve upon the linear correlation between the composite average water-level and the yearly means of the 300-month effective average precipitation-rate by adding an arbitrary constant to values of the former before determining their ratio to values of the latter. The best correlation was obtained by adding 15 feet to the composite average water-level. The ratio then became (61.65 ft)/(41.37 in/yr) = 1.490 ft/(in/yr). Values of composite average water-level for 1912 to 1918 and 1932 to 1942 adjusted in this manner are plotted in Figure 3 as open circles falling near the composite average water-level curve on the upper block of that diagram. Monthly values of effective average precipitation-rate adjusted in the converse manner are plotted on the lower block of Figure 2. The resulting curve runs approximately through the mean position of the curve of the composite average water-level.

The fact that the best correlation is obtained not by a simple proportion but that the addition of a constant is required may be attributed to the failure of conditions on Long Island to satisfy completely two of the basic assumptions of the theory. The first, and perhaps more important, is that "the effective thickness of saturated beds below sea-level is great compared to the maximum height of the water-table above sea-level so that the total thickness may be regarded as constant" [Part I, p. 565]. The second is that "the rate of accretion is constant for each of the successive periods and proportional to the average rate of precipitation during that period" [Part I, p. 567]. It was pointed out in Part I [p. 567] that a modified theory taking account of the lateral variation of thickness of the saturated beds leads to equations sufficiently near in form to those of the simple theory that the approximations of the latter may be accepted, especially in view of the empirical adjustment that is required. Taking another view in justification of the procedure followed, the best linear correlation between the composite average water-level and the effective average rate of precipitation was sought in order to improve upon extrapolations of water-level records into the past and yet to insure reasonable overall conformity between current water-level and rainfall-data as a basis upon which to work in analyzing short-term water-level fluctuations. Having accounted for the secular variations of ground-water level, we should be better prepared to proceed with the analysis, for example, of the annual phreatic cycle.

Referring again to Figure 2, and comparing the curve of composite average water-level with the curve for the 300-month effective average precipitation-rate adjusted linearly to the same scale, it may be remarked that although over a period of years the two curves agree on the average, in detail they do not agree. But the assumptions upon which the theory is based, especially the one regarding the proportionality between rates of precipitation and rates of accretion, are such that a closer agreement than that existing between these two curves is not to be expected. It was stated in Part I [p. 565] that "in the absence of large variations from year to year in the ratios to

precipitation of the surface-runoff and of the loss due to evaporation and transpiration, a graph of the effective average rate of precipitation theoretically should conform with a plotting of annual mean water-levels." Lack of conformity between the two curves on an annual basis, as plotted in Figure 3, may be attributed, therefore, to variation in the fractions of the yearly precipitation that are disposed of as runoff and as evaporation and transpiration. Similarly, the more evident lack of conformity between the same two curves plotted on a monthly basis in Figure 2 may be attributed to the greater month-to-month and seasonal variations in the same factors. Major causes of discrepancy are the occurrence of successive storms of high intensity, as illustrated by the record for 1938 and 1939 [13], and the prolongation of periods of drought, as for example in the late summer and fall of 1941.

An idea of the relative magnitude of the seasonal variation in evaporation and transpiration as reflected in the annual cycle of the water-level may be gained by comparing the amplitudes of the two curves referred to, particularly for the more or less "normal" years 1912 to 1915 and 1935 to 1937. According to the theory outlined in Part I, if, starting on a given day, for example at the phreatic high in the spring, all further accretion to the water-table were to cease, the water-level would begin to decline at a rate such that if this initial rate of decline were continued the water table would be reduced to sea level in the time $t_0 = (k\Delta t/2)$, which in this case is 12 or 13 years. Actually the rate of decline of the water-table during the late spring and early summer of the years cited was on the average about twice this theoretical maximum. Of course allowance should be made for the possibility that a more exact theory taking account of the non-linearity introduced by the variation in depth of flow would allow a higher rate of initial decline during a period of zero-accretion. Nevertheless, even with this in view it is suggested quite clearly that over a fair proportion of the annual cycle on Long Island the movement of moisture from the ground to the water-table is reversed. The rate of accretion thus becomes temporarily negative. The motivating processes are, of course, evaporation and transpiration. But the exact details of the mechanism of transfer remain to be elucidated.

In Figure 3 there is plotted a curve giving the cumulative departure of precipitation from the average rate at the Battery for the period 1826 to 1942 [14]. This may be compared with the graphs of the 25-year progressive average precipitation-rate and the 25-year effective average precipitation-rate. Of the three curves, that of the 25-year effective average correlates best with the composite average water-levels plotted as open circles. Unfortunately the water-level measurements only cover a range of secular fluctuation of about four feet in 47 feet, or less than ten per cent. However, we do have reports by the natives on the level of Lake Ronkonkoma going back to 1857. The statements given in Figure 3 are taken from the report of the BURR-HERING-FREEMAN Commission [15] referred to by LEGGETTE [16]. Making due allowance for the fallibility of memory, those reports check fairly well the probable trend of water-levels in those years inferred from the 25-year effective average precipitation-rate. The degree to which the level of Lake Ronkonkoma follows the trend of ground-water levels in the area to the west is seen in Figure 2, where a month-by-month record of the lake-level is given for recent years.

Having determined empirically the value of t_0, we are enabled crudely to check certain other factors to which it is related. In Part I, following equation (10), t_0 is designated as an abbreviation for $(4a^2S/\pi^2T)$, where a is the half-width of the hypothetically infinite strip, T is the transmissibility of the aquifer, which is assumed to be of great thickness, and S is the coefficient of storage, in this case an "effective porosity". From equation (2) of Part I, when $x = a$, $h_0 = (a^2W/2T)$. This gives the elevation of the water-table at the ground-water divide in terms of a, T, and W, the latter being the effective average rate of accretion to the water-table. Substituting in the foregoing expression for t_0 the value of (a^2/T) given by the last equation above

$$t_0 = (4S/\pi^2)(2h_0/W), \text{ or } W = (8Sh_0/\pi^2 t_0)$$

Now, it was found that $t_0 \cong 12.5$ years $\cong 4{,}600$ days. On Section A-A' (Fig. 1) $h_0 = 85$ feet (for $x = a$). And S may be taken as approximately 0.40. Thus $W = (8 \times 0.40 \times 85 \text{ ft})/(\pi^2 \times 4{,}600 \text{ days}) = 0.0060$ foot/day.

The effective average precipitation-rate is about 43 in/yr (average for the Battery and Setauket), or $\overline{R} = 0.0098$ foot/day. This would indicate that the average rate of accretion to the water-table is about 60 per cent of the average rate of precipitation. An earlier estimate placed this ratio for the island as a whole at about 44 per cent [17]. However, there is sufficient leeway in both estimates that the difference need not be considered significant.

the transmissibility of an equivalent aquifer of large thickness may now be determined:

$$T = (a^2W/2h_0) = (44{,}000^2 ft^2 \times 0.0060 ft/day)/(2 \times 85 ft) = 68{,}000 ft^2/day$$

The greatest uncertainty, perhaps, attaches to the proper value of thickness m. If it be assumed that the sands of Magothy age are effectively inter-connected with the water-table, then an average thickness of 500 feet might be taken as reasonable; whence the transmission-constant K = (T/m) = 140 ft/day. It should be emphasized, however, that the above value of T is only an apparent transmissibility. Moreover, the equating of the two expressions for (a^2/T) to determine W is not strictly valid and gives, therefore, only a rough approximation of the true average W.

The concept of effective average rate of precipitation might find useful application in the analysis of long-term records of "ground-water flow" in streams. Indeed, it would seem that a step toward bridging the gap between our understanding of infiltration and of ground-water runoff might be taken by setting up in the field a system of observation-wells and gaging-stations in as near an ideal area as possible--one that is not unduly complicated by effects of frost or snow-cover. If an area could be found in a humid climate where a nearby flat-lying bed-rock is covered more or less uniformly with sediments cut by parallel streams, the installation of a series of test-well profiles and rain-gages, with one or more pairs of gaging-stations, would provide sufficient control for a rational evaluation of ground-water runoff. One of the principal weaknesses of the present study on Long Island lies in the impracticability of measuring directly the ground-water that is discharged along the northern and southern shores of the Island. In the suggested test set-up these parallel shores would be replaced by effluent streams. The gain in flow per unit-length of reach would give, then, the desired measure of ground-water discharge.

Acknowledgment--The ground-water investigation of which this study forms a part is being conducted by the United States Geological Survey in cooperation with the New York State Water Power and Control Commission, with Nassau County, and with Suffolk County. The writer wishes to acknowledge the constructive criticism of M. L. BRASHEARS, Jr., under whose direction the work was done.

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WELL-DISCHARGE: A METHOD OF COMPUTING THE QUANTITY OF WATER DERIVED FROM STORAGE WITHIN A GIVEN RADIUS OF A DISCHARGING WELL

L. K. Wenzel and R. G. Kazmann

(Published with the approval of the Director, U. S. Geological Survey)

Formulas involving the discharge of wells are being given increasing use in quantitative ground-water hydrology. The formulas are generally used in one of two ways, namely: (1) To determine the coefficients of storage and transmissibility of water-bearing materials; or (2) to determine the drawdown of the ground-water level caused by the discharge of a well or group of wells. The formulas necessarily are based on assumptions of ideal conditions that are rarely found in nature; thus, much of the work of the ground-water hydrologist deals with interpreting the effect on the solutions given by the formulas of the differences between the field and assumed conditions.

The well-discharging formula that is commonly used at the present time was introduced by THEIS [see 1 of "References" at end of paper] and is commonly referred to as the non-equilibrium formula [2]. It is based on the following assumptions: (1) The water-bearing formation is homogeneous and isotropic;(2) the formation has an indefinite areal extent; (3) the discharging well penetrates the entire thickness of the formation, (4) the coefficient of transmissibility is constant at all places and at all times; (5) the discharging well has an infinitesimal diameter; and (6) water taken from storage by the decline in water-level is discharged instantaneously with the decline in head.

The non-equilibrium formula may be written

$$s = (114.6Q/T) \int_u^\infty (e^{-u}\, du/u)$$

where s = drawdown, in feet, of the piezometric surface of a well discharging at a uniform rate, Q = discharge of the well in gallons per minute, r = distance, in feet, from discharging well to point where the drawdown is measured, S = coefficient of storage of aquifer, t = time, in days, that the well has been discharging, T = coefficient of transmissibility in gallons per day, and $u = (1.87\, r^2\, S/Tt)$.

One of the most perplexing problems involved in the application of this formula to field-conditions is the effect of boundaries on the drawdown of the water-level. The formula is based on the assumption that the aquifer has an indefinite areal extent, whereas, in reality, all formations are limited in size. The discrepancy caused by boundaries is greater, of course, for formations of small extent than for formations of larger extent, and is greater for long than for short periods of pumping. The effect of boundaries is to increase the observed drawdown over that computed by the non-equilibrium formula. On the other hand, this effect is usually counteracted to some extent by recharge to the formation, inasmuch as the formula also assumes that there is no source of water except that which is contained in the formation at the time the well begins discharging. It is thus usually difficult to determine separately the effect of boundaries or the effect of recharge.

In an effort to aid in determining the effect of boundaries, the writers developed a formula for computing the quantity of water that is derived from storage within a given distance of a discharging well. The fundamental assumptions are the same as those given above for the non-equilibrium formula.

It is first necessary to determine the hydraulic gradient at any point on the cone of depression.

Starting with the equation

$$s = (114.6Q/T) \int_u^\infty (e^{-u}\, du/u) \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

let $u = br^2$, then $du = 2br\,dr$. Substituting, we obtain

$$s = (114.6Q/T) \int_{br^2}^\infty [(e^{-br^2}/br^2)\ d(br^2)]$$

Therefore

$$(ds/dr) = -(229.2Q/Tr)e^{-br^2}$$

The hydraulic gradient, $i = (ds/dr)$, therefore

$$i = -(229.2Q/Tr)e^{-u} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

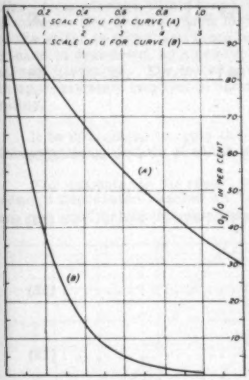

Fig. 1--Relationship of quantity of water entering cylinder and that discharged by well

The flow in gallons per minute at point r through a column of material the thickness of the aquifer and one foot wide is

$$q = -(Ti/1440) = -(T/1440)(229.2\,Q/Tr)\,e^{-u} \quad \ldots\ldots(3)$$

Through a cylindrical shell of aquifer, radius r, the rate of flow in gallons per minute is

$$Q_3 = 2\pi r q = \left\{[(2\pi r\,T)(229.2\,Q)]/(1440\,Tr)\right\} e^{-u} = Q e^{-u} \quad \ldots(4)$$

Therefore the ratio between the quantity of water entering the cylinder and the quantity of water discharged by the well is given by

$$(Q_3/Q) = e^{-u} \quad \ldots\ldots\ldots\ldots\ldots(5)$$

Figure 1 is a plat of this relationship for ease of computation. It affords a quick check as to whether or not the piezometric surface in the vicinity of a discharging well has reached equilibrium. When the value of u is less than about 0.1 the per cent of water coming from outside the given circle exceeds 90 and most likely the equilibrium-type formula may be safely applied to determine permeability and transmissibility.

The total flow to the well in t days, through the cylinder can be determined by integrating equation (4) with respect to t.

$$V_1 = 1440\,Q \int_0^t e^{-u}\,dt$$

Let $u = (a/t)$; then

$$V_1 = 1440\,Q \int_0^t e^{-(a/t)}\,dt \quad \ldots\ldots\ldots\ldots\ldots\ldots(6)$$

The following integration, concluding with equation (10) was furnished by Dr. W. D. LAMBERT of the United States Coast and Geodetic Survey. Let $x = (1/t)$ then $t = (1/x)$, $dt = -(dx/x^2)$. When $t = o$, $x = \infty$, $t = t$, $x = (1/t)$ and

$$V_1 = 1440\,Q \int_{\infty}^{1/t} [(-e^{-ax}/x^2)\,dx] \quad \ldots\ldots\ldots\ldots\ldots(7)$$

The formula for integration by parts is $\int udv = uv - \int vdu$; let $dv = (dx/x^2)$, $V = (1/x)$, $u = -e^{-ax}$, $du = ae^{-ax}dx$. Then

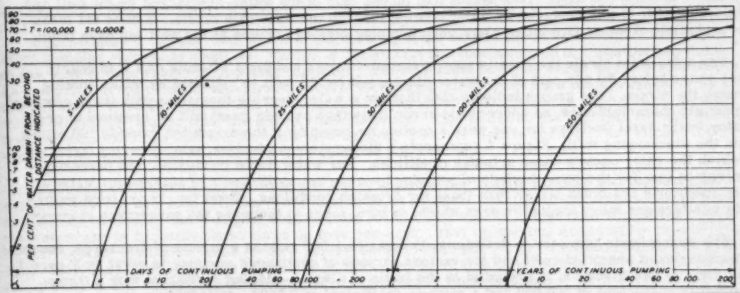

Fig. 2--Percentage of water drawn from beyond selected distances from discharged well for various periods of pumping

$$V_1 = 1440\,Q\left\{\left[-e^{-ax}(-1/x)\right]^{1/t}_{\infty} - \int_{\infty}^{1/t} -(1/x)\,a\,e^{-ax}\,dx\right\} \quad \ldots\ldots\ldots\ldots (8)$$

$$= 1440\,Q\left[te^{-a/t} + a \int_{\infty}^{1/t} e^{-ax}\left[d(ax)/ax\right]\right. \quad \ldots\ldots\ldots\ldots\ldots (9)$$

Reversing limits of integration, equation (9) becomes

$$V_1 = 1440\,Q\left[te^{-(a/t)} - a(-Ei - a/t)\right] \quad \ldots\ldots\ldots\ldots\ldots (10)$$

Substituting $u = (a/t)$

$$V_1 = 1440\,Q\left[te^{-u} - tu(-Ei - u)\right]. \quad \ldots\ldots\ldots\ldots\ldots (11)$$

The total quantity of water discharged by the well in t days is

$$V_2 = 1440\,Qt \quad \ldots\ldots\ldots\ldots\ldots (12)$$

The total quantity taken from storage within the cylinder is

$$V_3 = (V_2 - V_1) \quad \ldots\ldots\ldots\ldots\ldots (13)$$

$$V_3 = 1440\,Qt - 1440\,Q\left[te^{-u} - tu(-Ei - u)\right] \quad \ldots\ldots\ldots\ldots (14)$$

$$V_3 = 1440\,Qt\left[1 - e^{-u} + u(-Ei - u)\right] \quad \ldots\ldots\ldots\ldots (15)$$

The ratio between the total quantity of water taken from outside the cylinder of given radius and the total discharged by the well is

$$V_1/1440\,Qt = 1 - e^{-u} + u(-Ei - u). \quad \ldots\ldots\ldots\ldots (16)$$

The ratio between the total quantity of water coming from storage within the cylinder to the total quantity pumped is P.

$$P = e^{-u} - u(-Ei - u). \quad \ldots\ldots\ldots\ldots\ldots (17)$$

The percentages of water drawn from beyond selected distances from the discharging well (radii of the cylindrical B-sections of water-bearing material) for various periods of pumping are illustrated by the graphs in Figure 2. The graph has been prepared for a water-bearing material whose transmissibility coefficient is 100,000 and whose storage-coefficient is 0.0002. The graphs do not mean that particles of water at or beyond a certain distance are discharged by the well within a given period. For example, the graphs indicate that 50 per cent of the water discharged by a well is assumed by the non-equilibrium formula to percolate to the well from beyond a distance of five miles in about ten days. This means that 50 per cent of the water discharged by the well and originating near it was replaced by water coming through the five-mile circle. It does not mean that a particle of water five miles away when pumping started arrived at the well ten days later.

For a ten-mile circle the time is approximately 40 days and for a 50-mile one it is nearly three years before 50 per cent of the water discharged by the well is replaced by water coming through the circle. The graphs indicate also that for a water-bearing formation with these assumed hydrologic characteristics, no appreciable error (less than two per cent) will be involved in predicting water-level declines for one year's continuous pumping if the formation extends 100 miles from the discharging well. Figure 2 represents a moderately productive water-bearing material in which the water occurs under artesian conditions. For water-table conditions, the percentage of error is less for the same periods of pumping because the coefficients of storage for water-table conditions are much larger than those for artesian conditions. However, in practice water-table aquifers are more limited in area which, in turn, tends to increase the percentage of error.

The approximate increase in drawdown, in feet per 1,000 gallons a minute of discharge, caused by boundaries of specified radii and for various periods of continuous pumping is given in Figure 3. This Figure, like Figure 2, is prepared on the basis of a water-bearing formation with a transmissibility coefficient of 100,000 and a storage-coefficient of 0.0002. This Figure was prepared by assuming that the water which would have been drawn from storage beyond the specified radii was

taken from storage within these radii by a uniform decline of the water-level over the cone of depression. The Figure shows that although the non-equilibrium formula assumes that 50 per cent of the water is withdrawn from beyond five miles in about ten days of continuous pumping, the increase in drawdown, as a result, amounts to only slightly more than two feet per 1,000 gallons a minute discharge. The increase in drawdown per 1,000 gallons a minute of discharge would amount to approximately two feet in about three years, providing the water-bearing material extended 50 miles.

It is instructive to apply the equations derived in this paper to the results of pumping-test investigations, details of which have been publi..ed [2].

For example, in the report of the Grand Island (Nebraska) investigations, it is stated that the cone of depression reached an "equilibrium-form" for a radius of 200 feet after two days' pumping and equilibrium-formulas were applied to determine permeability. Using the figures given in

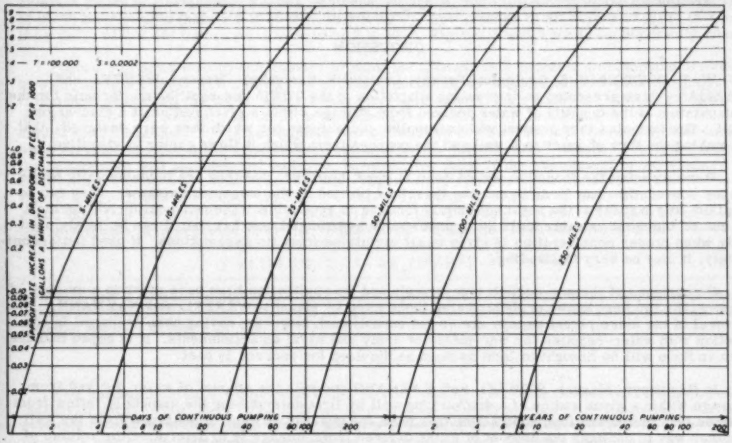

Fig. 3--Approximate increases in drawdown caused by specified radii of boundaries and for various periods of pumping

the paper: r = 200, S = 0.217, T = 94,278, t = 2, we get $u = 1.87(200)^2(0.217)/(94,278 \times 2) = 0.0862$.

From Figure 1 the per cent of water percolating from beyond the 200-foot circle two days after pumping started is about 92. Thus it is shown that the conclusion as to "equilibrium-form" of the cone of depression is probably justified. The maximum possible error in the permeability as computed by an equilibrium-formula due to a changing form of the cone of depression is under ten per cent. It would appear that the transmissibility determined from the equilibrium-formula would be slightly higher than the true transmissibility. This is due to the fact that an equilibrium-type formula assumes that all the water discharging from the well is coming from without the circle of given radius whereas actually only about 92 per cent is.

However, considering the limiting method of applying the THIEM formula and the fact that points within the 200-foot cylinder were also used, it is likely that the error in the value of transmissibility caused by the changing shape of the cone of depression is less than the eight per cent maximum and is probably about three or four per cent. That is, the transmissibility as computed by the limiting method is three or four per cent higher than the "true" transmissibility. It is also very likely that in practice the magnitude of the error from this source is of less importance than errors due to the complexity of geology in the area under consideration.

A similar computation for the Kearny test shows that over 97 per cent of the water came from beyond a 200-foot cylinder in one day. In the Gothenburg test about 96 per cent of the water came from beyond a 200-foot cylinder in one day. In the Scottsbluff test nearly 92 per cent of the water discharged came from beyond a 500-foot cylinder after only 15 hours of pumping.

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DISCUSSION

W. F. GUYTON (U. S. Geological Survey, Louisville, Kentucky)--Messrs. WENZEL and KAZMANN have presented an interesting adaptation of the THEIS non-equilibrium formula for the computation of the quantity of water derived from storage within a given radius of a discharging well. The formulas they present will accomplish the purpose for which they were designed--that of making the flow of water to a well and the sources from which it flows easier to visualize.

Persons using the formulas should keep in mind, however, that they are fundamentally based on the non-equilibrium formula and are therefore limited by the same assumptions. They can be applied only in so far as the non-equilibrium formula is applicable. The non-equilibrium formula is one of the most valuable tools the ground-water hydrologist now has, but it can be safely used only when proper consideration is given to all variations from its assumptions. If used indiscriminately, it may be very misleading.

Discussions of the non-equilibrium formula and its application have been given in a number of papers, the two best known probably being those cited by Messrs. WENZEL and KAZMANN. Several of the more recent papers are as yet unpublished, however, having been prepared in connection with water-supplies for war-plants or army and naval establishments. It is hoped that the data in them will be brought to light as soon as the need for secrecy is past.

In this paper, Messrs. WENZEL and KAZMANN compute the amount of water derived from storage within a given radius of a discharging well by first determining the amount of inflow from outside that radius and then subtracting this from the quantity of water discharged from the well. Another way to compute the amount of water derived from storage is to determine the volume of the cone of depression within the given radius and multiply this by the storage-coefficient. Following is a derivation of the authors' equation (15), based on the volume method.

In addition to the authors' nomenclature, let V = the volume (in cubic feet) of the cone of depression within the given radius, let R = the given radius (in feet), and let $m = (1.87R^2/Tt)$ and $m' = (1.87r^2S/Tt)$

$$V = (\pi R^2)(114.6Q/T) \int_m^\infty e^{-u}\,du/u + \int_0^R \pi r^2\,ds$$

$$ds = (114.6Q/T)(e^{-u}\,du/u)$$

$$du = (1.87S/Tt)(2r\,dr)$$

$$V = (\pi R^2)(114.6Q/T) \int_m^\infty e^{-u}\,du/u + \int_0^R (\pi r^2)(114.6Q/T)\,e^{-m'}[2r\,dr\,(1.87S/Tt)/m']$$

$$= (\pi R^2)(114.6Q/T) \int_m^\infty e^{-u}\,du/u - (114.6Q\pi t/1.87S) \int_0^R e^{-m'}(-1.87S/Tt)\,2r\,dr$$

$$= (\pi R^2)(114.6Q/T) \int_m^\infty e^{-u}\,du/u - (114.6Q\pi t/1.87S)[e^{-m'}]_0^R$$

$$= (\pi R^2)(114.6Q/T) \int_m^\infty e^{-u}\,du/u + (114.6Q\pi t/1.87S)(1 - e^{-m})$$

$$V = (V_3 / 7.48S)$$

$$V_3 = [(7.48S)(\pi R^2)(114.6Q)/T] \int_m^\infty e^{-u} du/u + [(7.48S)(114.6Q\pi t)/1.87S](1 - e^{-m})$$

$$= 1440\ Q\, m \int_m^\infty (e^{-u} du/u) + t - te^{-m}$$

$$= 1440\ Qt\left\{1 - e^{u}[-Ei(-u)]\right\} \quad \ldots\ldots\ldots\

C. E. JACOB (U. S. Geological Survey, Jamaica, New York)--As indicated by the title, this paper by WENZEL and KAZMANN presents the derivation of the equation for the proportion of the total discharge of a well that is derived from artesian storage within a given radial distance of the well. The well is assumed to pump continuously at a steady rate from an infinite artesian aquifer. Accordingly, at any time after pumping begins the total volume of water discharged up to that time equals the volume derived from storage within the specified radius plus the volume derived from storage beyond that radius, there being no external source of water. The writers present two interesting sidelights of this main idea.

First, in the derivation of the relation sought for they find it expedient to use the expression for the ratio between the rate of flow through a given circle concentric with the well and the discharge-rate of the well. This expression they apply to estimate the error of permeability-values determined by the THIEM method. For example, from their Figure 1 the writers find that the maximum error of permeability or transmissibility-determinations by the THIEM method in the Grand Island Test, with r less than 200 feet and with t = two days, is eight per cent. This error is actually eight per cent of the apparent transmissibility, or more nearly ten per cent of the true value. For, from equation (4) the radial flow at a distance r is Qe^{-u}, and this equals $-(2\pi rT)(\partial s/\partial r)$. But in terms of the limiting value of apparent transmissibility (that is, the value of transmissibility determined by the THIEM method from two very closely spaced wells at the distance r) the discharge of the well is

$$Q = -2\pi rT'(\partial s/\partial r) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (18)$$

Eliminating Q from this and the foregoing relation, we find that

$$T'/T = 1/e^{-u} = e^{u} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (19)$$

or the relative error of the transmissibility-determination is

$$[(T' - T)/T] = e^{u} - 1 \text{ [not } (1 - e^{-u})] \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (20)$$

In the example referred to the difference here is small but nevertheless significant: $(1 - e^{-u}) = 0.083$ or 8.3 per cent and $(e^{u} - 1) = 0.090$ or 9.0 per cent. But the u in the writers' computations has an apparent value and not the true value of transmissibility in the denominator. Further adjustments for this factor indicate that the error is even greater, probably about ten per cent in this case.

In this connection the writer has found useful the graph reproduced here as Figure 4. This shows the relative error of the apparent transmissibility as determined by the THIEM method, for different combinations of the distances r_1 and r_2 and for different values of (r_2/a), which equals $\sqrt{u_2}$, corresponding to the outer distance. These curves were computed as follows: The true transmissibility in terms of drawdowns at two different distances is

$$T = Q[-Ei(-u_1) + Ei(-u_2)]/4\pi(s_1 - s_2) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (21)$$

As determined by the THIEM method the apparent transmissibility is

$$T' = Q \log_e(r_2/r_1)/2\pi(s_1 - s_2). \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (22)$$

Then the ratio of the apparent to the true transmissibility is

$$(T'/T) = 2 \log_e(r_2/r_1)/[Ei(-u_2) - Ei(-u_1)]. \quad \ldots\ldots\ldots\ldots\ldots\ldots (23)$$

and from this values of $[(T' - T)/T]$ shown on Figure 4 may be determined.

In the example referred to $u_2 = 0.0862$, or $(r_2/a) = \sqrt{u_2} = 0.294$. Finding the appropriate point on the line for $(r_1/r_2) = 1$ on Figure 4, the maximum error of transmissibility determinations by the THIEM method again appears to be 9.0 per cent. A second adjustment shows that the maximum error is more than 9.8 per cent of the true transmissibility. However, the average error of the six permeability-determinations by the THIEM method based on all possible combinations of the distances 50, 100, 150, and 200 feet appears to be about 3.5 per cent before adjustment, checking the writers' estimate on this point.

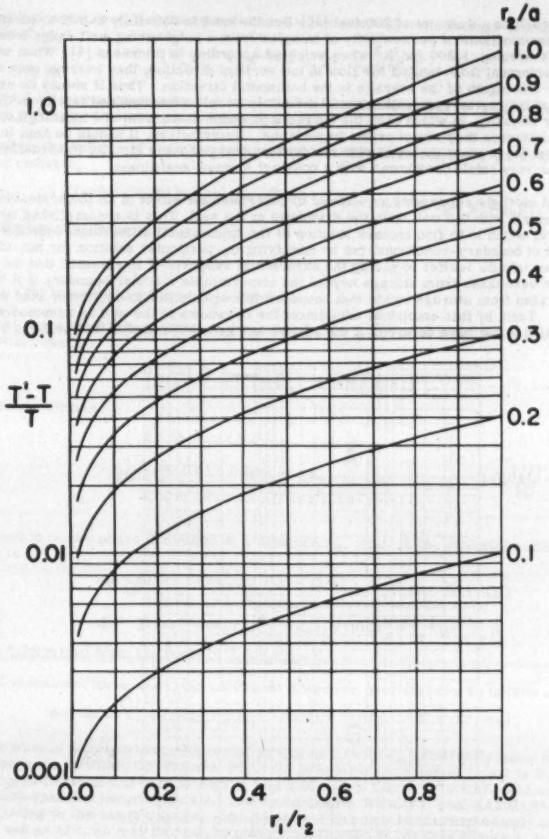

Fig. 4--Relative error of apparent transmissibility determined by Thiem method, resulting from non-steady character of radial flow

A precise value of T could be obtained by successive approximations using the curves in Figure 4, or in the limiting case using equation (20). But, as pointed out by the writers, very often in practice errors such as just discussed are small compared to errors arising from the complexities of the structure and from other causes. Indeed, in the Grand Island Test the partial penetration of the pumping well alone invalidates the THIEM equation [7] and introduces serious errors into transmissibility-determinations based thereon--errors probably of the order of 50 per cent. The pumping well penetrated only the top 40 feet of a 100-foot sand [8], and as the drawdown just outside the well was ten feet [9] the effective fractional penetration was probably less than 35 per cent. Consequently, even if the sand were isotropic the disturbing effect of the converging flow

would extend nearly to a distance of 200 feet [10]. But the sand is definitely known to be stratified. Laboratory determinations of permeability of samples from a neighboring well range from 2 to 4,350 gpd/ft^2, averaging 1,200 gpd/ft^2 when weighted according to thickness [4]. When weighted according to reciprocal flow-lengths for flow in the vertical direction, they average only about 150 gpd/ft^2, or one-eighth of the average in the horizontal direction. Thus it should be expected that the effect of the partial penetration would definitely be felt a few hundred feet from the well, in even greater intensity, in which case the corrections under discussion are meaningless. However, in many instances they are of prime importance. Nevertheless, it should be kept in mind that at the outset the present theory of non-steady flow does not apply strictly to unconfined aquifers, except for very small drawdowns with a constant storage-coefficient.

The second sidelight represents an attempt to determine the effect of an impermeable circular boundary concentric with the well upon the drawdown at the well. This is accomplished not by the usual procedure, which is to find another solution of the fundamental differential equation satisfying the new set of boundary-conditions, but by modifying the particular solution for non-steady radial flow in an infinite aquifer involving the exponential integral. It is assumed that the water that would have been taken from storage beyond the impermeable circular boundary if it had not been there is taken from storage inside that boundary through a uniform decline of head over the enclosed area. Then, by this empirical adjustment the drawdown at the well is assumedly equal to the drawdown that would have occurred if the aquifer had been infinite plus this uniform decline (Δs).

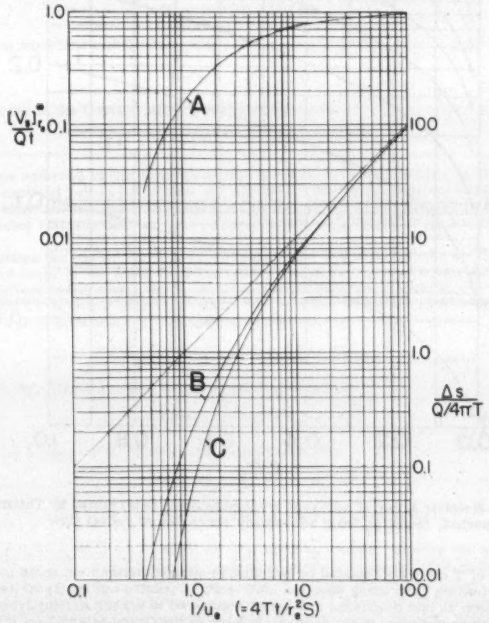

Fig. 5--Graph showing additional drawdown over that for an infinite aquifer caused by an impermeable circular boundary concentric with the well according to Wenzel and Kazmann (B), according to exact solution by Muskat (C); curve (A) shows proportion of total volume discharged by well that is derived from storage beyond a given distance

According to equation (17) the total volume of water derived from storage beyond the distance r_e up to time t is

$$[V_s]_{r_e}^{\infty} = [e^{-u_e} + u_e \, Ei(-u_e)]Qt \quad \ldots\ldots\ldots\ldots\ldots\ldots (24)$$

In Figure 5 this equation is plotted in non-dimensional form as Curve A--a useful generalized reproduction of the several curves in Figure 2.

Distributing the volume of storage given by equation (24) uniformly over the area enclosed by the circle of radius r_e

$$\Delta s = [e^{-u_e} + u_e Ei(-u_e)]Qt/\pi r_e^2 S = (Q/4\pi T)[e^{-u_e}/u_e + Ei(-u_e)] \quad \ldots\ldots\ldots (25)$$

or, in non-dimensional form

$$\Delta s/(Q/4\pi T) = e^{-u_e}/u_e + Ei(-u_e) \quad \ldots\ldots\ldots\ldots\ldots\ldots (26)$$

Equation (26) is plotted as Curve B in Figure 5.

The exact solution of this problem is given by MUŠKAT [8]. It is required to find a solution of the differential equation

$$[\partial(r\,\partial s/\partial r)/r\,\partial r] = (S/T)(\partial s/\partial t) \quad \ldots\ldots\ldots\ldots\ldots (27)$$

satisfying the conditions

$$\left.\begin{array}{l} s = 0 \text{ for } t = 0 \\ (\partial s/\partial r) = 0 \text{ for } r = r_e \\ r(\partial s/\partial r) \rightarrow -(Q/2\pi T) \text{ as } r \rightarrow 0 \end{array}\right\} \quad \ldots\ldots\ldots\ldots (28)$$

Expressed in terms of the drawdown at a distance r_w, equal to the effective radius of the well, the solution is

$$s_w = (Q/2\pi T)[\log_e(r_e/r_w) - (3/4) + (1/2u_e) - 2\Sigma]$$

where

$$\Sigma = \sum \exp\left\{[-(\alpha_n r_e)^2/4u_e]\right\} / [(\alpha_n r_e)^2 J_o^{\,2}(\alpha_n r_e)] \quad \ldots\ldots\ldots (29)$$

the α_n being determined from the roots of $J_1(\alpha_n r_e) = 0$.

In non-dimensional form, then, the additional drawdown over that for an infinite aquifer is

$$\Delta s/(Q/4\pi T) = 2\log_e(r_e/r_w) - (3/2) + (1/u_e) - 4\Sigma + Ei(-u_w) \quad \ldots\ldots\ldots (30)$$

This equation is also plotted in Figure 5, as Curve C, with r_w arbitrarily taken as one foot. In the first example to which the writers' Figure 3 is applied the value of $(1/u_e)$ is 3.83. The corresponding ordinate of Curve B in Figure 5 is 1.95 and of Curve C is 1.57. The additional drawdown per 1,000-gpm discharge is thus 2.2 feet according to WENZEL and KAZMANN, or about 1.8 feet according to the exact solution. The relative difference is correspondingly much greater for smaller values of t, as may be seen by comparing Curves B and C in Figure 5, but as time goes on the two curves approach one another.

The writers speak of the "effect of boundaries" as contrasted to the "effect of recharge." But since recharge must occur at a boundary of the aquifer, if it occurs, it would seem that they are attempting rather to evaluate the effect of an impermeable boundary, along which the normal component of gradient must vanish. This boundary-condition is to be contrasted to those that might obtain along a permeable boundary, where, as a simple example, the head might remain constant, or where, in another case, the flow per unit-length of boundary might remain constant. The writers have treated a very special case, that of a single well in the center of a closed circular basin. Generally in practice such simple geometry is not found, but recourse may be had to the method of GREEN'S functions to solve other more practical cases [13]

In deriving the expression for the hydraulic gradient in non-steady radial flow, equation (2), the writers work backwards from the exponential integral. Consequently their treatment is perhaps not easily followed by one unfamiliar with the original derivation. A more direct approach [10] is made by returning to the basic differential equation [equation (27)] and determining $(\partial s/\partial r)$ to satisfy also the conditions

$$\left.\begin{aligned} (\partial s/\partial r) &= 0 \text{ for } t = 0 \\ (\partial s/\partial r) &= -(Q/2\pi rT) \text{ for } t = \infty \\ (\partial s/\partial r) &= 0 \text{ for } r = \infty \end{aligned}\right\} \quad \ldots\ldots\ldots\ldots\ldots\ldots (31)$$

at the same time having $(\partial s/\partial t)$ satisfy the identity

$$[\partial(\partial s/\partial t)/\partial r] \equiv [\partial(\partial s/\partial r)/\partial t] \quad \ldots\ldots\ldots\ldots\ldots\ldots (32)$$

These conditions are met by

$$(\partial s/\partial r) = -(Q/2\pi rT) \exp(-r^2S/4Tt) \quad \ldots\ldots\ldots\ldots\ldots\ldots (33)$$

as given by the writers' equation preceding equation (2). (Dimensional reasoning is employed to advantage here to determine the proper combination of r, t, S, and T in the exponential.)

Incidentally, it would seem that in view of all the uncertainties involved the transmissibility should not be carried out to five digits. In the data for Grand Island the writers give T = 94,278 in gpd/ft. Even disregarding the imperfections of the theory and the various corrections that are needed, in view of inaccuracies of discharge and water-level measurements alone there can be but two significant figures in this case. When the need for correcting for non-steady flow is acknowledged the transmissibility should be represented perhaps as 90,000 ± 10,000 gpd/ft. And when the partial penetration of the pumping well is taken into account T should more nearly approach 200,000 gpd/ft than 100,000 gpd/ft.

References

[7] MORRIS MUSKAT, The flow of homogeneous fluids through porous media, McGraw-Hill, 1937, footnote p. 368.
[8] U. S. Geol. Surv., W.-S. Paper 887, p. 118.
[9] U. S. Geol. Surv., W.-S. Paper 887, p. 150.
[10] About twice the thickness of sand; see MUSKAT, Idem, p. 271.
[11] U. S. Geol. Surv., W.-S. Paper 679-A, p. 47.
[12] MUSKAT, Idem, p. 657.
[13] MUSKAT, Idem, p. 661, also Physics, v. 6, p. 27, 1935.
[14] Trans. Amer. Geophys. Union, p. 579, 1940.

L. K. WENZEL and R. G. KAZMANN (authors' closure)--Mr. JACOB'S discussion is a definite contribution to transmissibility-determination techniques. However, the first part of his discussion, dealing with corrections to be applied to the results of the THIEM method while distinctly useful, is based on a misunderstanding probably caused by a bit of unintentionally clumsy phraseology in the original paper. The writers never intended to propose an exact method of correcting transmissibilities as determined by the THIEM method. It was desired to make a rough check as to the state of equilibrium reached during a pumping test, using the results obtained from that test. The method was evolved for that purpose alone. As Mr. JACOB points out, (e^u-1) gives an exact correction if applied several times and this expression should be used.

With regard to the second point raised, the curves derived were merely intended as approximations. It is very gratifying to note that the writers' engineering approximation and the more refined MUSKAT-JACOB analysis coincide for the larger values of time. It is these larger values of time which enter into long-term predictions. For small values of t, use of the approximation gives larger values of drawdown and is, therefore, on the safe side.

With regard to the last comment on expressing T as 94,278 in gpd/ft, the writers have found that when a numerical example is given, it should be carried out beyond the limits of accuracy indicated by the data in order that the reader who tries to check the computation and is unfamiliar with the limits of accuracy involved may do so. Once the reader has obtained the same numerical

answer it is certain that he has followed the procedure given in the paper and then questions of limits of accuracy may be logically raised.

CATION-EXCHANGE IN GROUND-WATER CONTAMINATED WITH SEA-WATER NEAR MIAMI, FLORIDA

S. K. Love

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A comprehensive investigation of the ground-water resources of southeastern Florida by the United States Geological Survey from 1939 to 1944 has yielded a large amount of information about the quantity and quality of surface- and ground-waters available for municipal, industrial, and agricultural use in the area.

In connection with studies of the chemical character of ground-water in areas along the coast in and near Miami where the ground-water is contaminated with sea-water, it was found that the composition of the contaminated water differed considerably from the composition of simple mixtures of ground-water and sea-water. Differences in the composition of salty ground-water in southern Florida have also been observed by SANFORD [see 1 of "References" at end of paper] and STRINGFIELD [2]. It appears that the observed differences in the Miami Area can be explained as the result of cation-exchange.

The coastal area near Miami in which all of the samples were collected is shown in Figure 1. Included also in this Figure are isochlors in the contaminated area which are based on analyses of about 140 water-samples collected in January, 1943. The 25-parts-per-million isochlors represent the approximate limit of detectable salt-water penetration.

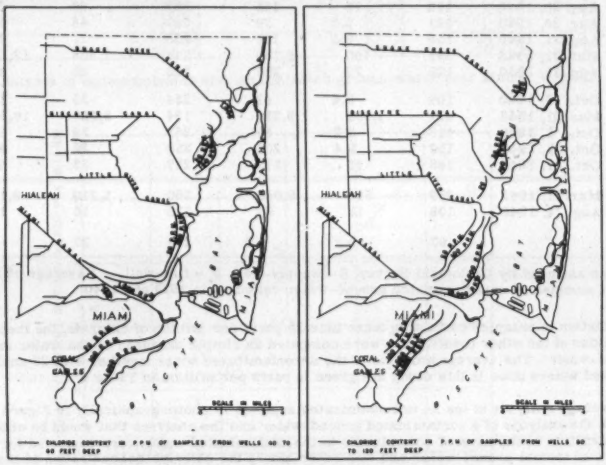

Fig. 1--Isochlors in the Miami Area based on analyses of ground-water samples, January 1943

Samples of uncontaminated ground-water collected from wells about 40 to 120 feet deep in the Miami Area were found to be relatively uniform in composition. Because of this uniformity an average of 34 analyses of samples collected from typical wells is assumed to represent the average composition of ground-water in the area. Using the chloride-concentration as an index of the degree

Table 1--Analyses of contaminated ground-water near Miami, Florida, with an average of analyses of uncontaminated water

(Parts per million)

Well No.[a]	Date collection	Calcium (Ca)	Magnesium (Mg)	Sodium, potassium (Na + K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
S - 4	Dec. 9, 1939	159	16	175	256	81	389
S - 4	Sep. 25, 1940	142	11	125	264	67	273
S - 13	Dec. 9, 1939	134	37	350	272	120	638
S - 14	Dec. 9, 1939	113	21	158	278	86	279
S - 15	Dec. 9, 1939	118	10	44	281	47	108
S - 46	Apr. 1, 1943	217	350	3,040	243	768	5,380
S - 90	Apr. 1, 1943	319	762	6,450	233	1,610	11,400
S - 94	Apr. 1, 1943	291	669	5,650	240	1,410	10,000
S - 112	Oct. 2, 1940	106	9.0	97	248	40	189
S - 145	Oct. 2, 1940	102	35	256	264	70	472
S - 150	Oct. 3, 1940	124	8.5	132	252	21	285
S - 278	Oct. 11, 1940	135	5.4	50	284	25	148
S - 301	Oct. 15, 1940	116	10	58	269	83	106
F - 2	Aug. 30, 1940	98	9.8	58	252	49	109
F - 3	Dec. 20, 1939	132	21	226	244	95	432
F - 3	Aug. 30, 1940	112	18	185	257	80	328
F - 4	Aug. 30, 1940	121	9.3	70	257	48	165
F - 12	Aug. 31, 1940	156	9.1	106	255	71	265
F - 101	Mar. 31, 1943	351	795	6,730	244	1,598	12,000
F - 117	Aug. 31, 1940	125	29	255	282	85	472
F - 131	Oct. 3, 1940	109	5.4	47	254	33	109
F - 143	Mar. 31, 1943	411	1,103	9,310	184	2,296	16,500
F - 155	Oct. 3, 1940	118	6.2	80	261	29	177
F - 173	Oct. 12, 1940	157	9.4	204	258	29	448
F - 173	Oct. 31, 1940	165	11	215	257	33	482
F - 198	Mar. 31, 1943	359	596	5,090	260	1,210	9,180
F - 299	Aug. 24, 1940	108	11	95	320	10	177
b	b	93	5.2	9.5	268	27	18

[a]Numbers assigned by Geological Survey; S = supply-well, F = fire-well. [b]Average of 24 analyses of samples of uncontaminated ground-water collected in 1939 and 1940.

of contamination in samples containing more than 25 parts per million of chloride, the theoretical concentrations of the other constituents were computed as simple mixtures of sea-water and normal ground-water. The average analysis of the uncontaminated water together with 27 analyses of contaminated waters used in this study are given in parts per million in Table 1.

The average analysis of the 24 uncontaminated samples is shown graphically in Figure 2, together with the analysis of a contaminated ground-water and the analyses that would be obtained if the concentrations of the several constituents in the contaminated water were computed for a simple mixture of normal ground-water and sea-water having the chloride-concentration of the sample. The analysis of the actual water shows that the concentration of calcium is larger and the concentrations of magnesium and sodium are smaller than are required by the computed analysis.

Since a study of the chemical reactions involves equivalent amounts of the ions taking part in the reactions, the following discussion deals with concentrations of chemical constituents expressed in equivalents per million. Deviations of actual anion-concentrations from the computed values were usually small and showed no tendency to be positive or negative. Deviations of actual concentrations of the cations from the computed values are given in Table 2.

Deviations in calcium concentrations were positive whereas deviations in magnesium and sodium concentrations were negative for all of the analyses given in Table 2. Although for many of the individual analyses the gain in calcium is not exactly offset by a corresponding loss in magnesium and sodium, nevertheless, when the gains in calcium are plotted against the sum of the

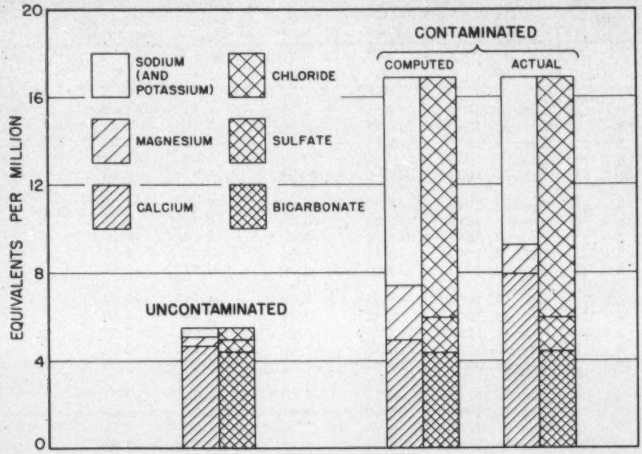

Fig. 2--Analyses of uncontaminated and contaminated ground-water near Miami, Florida

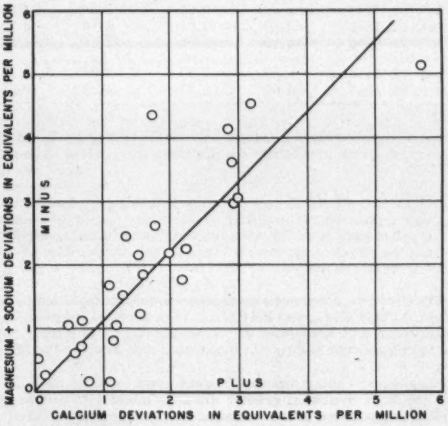

Fig. 3--Deviations of cation-concentrations in contaminated ground-water from computed cation-concentrations

Table 2--Deviations of cation concentrations from computed values for contaminated ground-water near Miami, Florida

(Equivalents per million)

Well No. (1)	Date collection (2)	Calcium (Ca) (3)	Magnesium (Mg) (4)	Sodium, potassium (Na + K) (5)	Sum [(4) + (5)] (6)
S - 4	Dec. 9, 1939	+2.99	-1.15	-1.91	-3.06
S - 4	Sep. 25, 1940	+2.25	-0.99	-1.26	-2.25
S - 13	Dec. 9, 1939	+1.55	-0.74	-0.48	-1.22
S - 14	Dec. 9, 1939	+0.80	-0.16	0.00	-0.16
S - 15	Dec. 9, 1939	+1.15	-0.08	-0.74	-0.82
S - 46	Apr. 1, 1943	+1.75	-1.65	-2.71	-4.36
S - 90	Apr. 1, 1943	+1.79	-0.24	-2.38	-2.62
S - 94	Apr. 1, 1943	+1.54	-0.08	-2.08	-2.16
S - 112	Oct. 2, 1940	+0.50	-0.66	-0.39	-1.05
S - 145	Oct. 2, 1940	+0.05	0.00	-0.52	-0.52
S - 150	Oct. 3, 1940	+1.35	-1.19	-1.26	-2.45
S - 278	Oct. 11, 1940	+2.00	-0.71	-1.48	-2.19
S - 301	Oct. 15, 1940	+1.10	-0.08	-0.09	-0.17
F - 2	Aug. 30, 1940	+0.15	-0.09	-0.18	-0.27
F - 3	Dec. 20, 1939	+1.60	-0.98	-0.87	-1.85
F - 3	Aug. 30, 1940	+0.70	-0.66	-0.05	-0.71
F - 4	Aug. 30, 1940	+1.30	-0.47	-1.05	-1.52
F - 12	Aug. 31, 1940	+2.94	-1.06	-1.91	-2.97
F - 101	Mar. 31, 1943	+2.90	-0.74	-2.88	-3.62
F - 117	Aug. 31, 1940	+1.20	-0.50	-0.56	-1.06
F - 131	Oct. 3, 1940	+0.70	-0.46	-0.66	-1.12
F - 143	Mar. 31, 1943	+2.19	-0.16	-1.62	-1.78
F - 155	Oct. 3, 1940	+1.10	-0.81	-0.87	-1.68
F - 173	Oct. 12, 1940	+2.84	-2.03	-2.13	-4.16
F - 173	Oct. 31, 1940	+3.19	-2.06	-2.48	-4.54
F - 198	Mar. 31, 1943	+5.69	-1.32	-3.82	-5.14
F - 299	Aug. 24, 1940	+0.60	-0.42	-0.22	-0.64

losses in magnesium and sodium for the 27 analyses as shown in Figure 3, the plot strongly suggests that, on the average, gains in calcium are approximately offset by losses in magnesium and sodium.

Extensive investigations in the field of soil-chemistry have shown that soil-colloids, including clay and organic components, possess the property of adsorbing one or more cations from water-solutions in exchange for other cations under suitable conditions. Comparatively little has been done, however, in studying the effect of cation-exchange on the composition of the water from which the adsorbed cations were derived.

MURRAY and IRVINE [3] found evidence of changes in the composition of sea-water in blue muds on the ocean bottom. FOSTER [4] and REVELLE [5] attributed changes in the composition of ground-waters contaminated with sea-water to cation-exchange. In none of these reports, however were the changes in composition similar to those observed in and near Miami.

In the Miami Area sea-water contamination has been observed only in wells within about two miles of the coast-line and for a somewhat greater distance inland along some of the tidal canals. Alteration in the chemical composition of the contaminated waters must, therefore, take place within this narrow coastal strip. Changes are presumably the result of cation-exchange which takes place between the magnesium- and sodium-ions in the water-mixtures and the calcium-ions

adsorbed on the clay or organic colloids in the ground.

Examination of well-cuttings obtained during the drilling of test-wells showed little evidence of clays in the highly permeable Tamiami formation in the Miami Area. However, since practically all normal ground-water is rather highly colored with organic matter, it may be that organic colloids are largely responsible for the cation-exchange.

Regardless of whether clay or organic colloids are responsible for the exchange, it is fairly certain that the active component in the uncontaminated area is saturated with respect to the calcium-ion. In earlier geologic history the whole area was submerged beneath the sea and therefore was saturated with sea-water. After emergence from the sea, the salty water was gradually flushed out of the highly permeable Tamiami formation by meteoric water. As the meteoric water came in contact with the lime-rock at shallow depths along the coast, some of the limestone was dissolved in the presence of carbon dioxide to form soluble calcium bicarbonate. During this leaching and flushing the colloids which were saturated with respect to magnesium- and sodium-ions were thus brought into contact with water containing calcium as its chief basic constituent. Cation-exchange took place leaving the colloids saturated with respect to calcium-ions while the magnesium- and sodium-ions released by the exchange were removed from the aquifer by the flushing action.

When the exchange-process is reversed by new intrusions of sea-water, the active colloids give up calcium-ions in exchange for the magnesium- and sodium-ions in the sea-water. The resulting concentration of cations in the contaminated water tend to be higher in calcium and lower in magnesium and sodium than would be expected from simple mixtures of ground-water and sea-water.

During periods of drought when the water-table is below normal, the landward movement of salt water appears to bring about an exchange of calcium-ions adsorbed on the clay and organic colloids for magnesium- and sodium-ions in the sea-water. During rainy periods, on the other hand, when the water-table is above normal, the seaward movement of the salty water is apparently accompanied by the reverse process of cation-exchange.

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DISCUSSION

OSCAR C. MAGISTAD (Director, U. S. Regional Salinity Laboratory, Bureau of Plant Industry, Soils and Agricultural Engineering, Riverside, California)--Mr. LOVE has accounted for the difference in actual and calculated ground-water analyses near Miami, Florida, on the basis of base-exchange. As shown in his Figure 3, the sum of decreases in Mg, Na, and K is approximately equal to the increases of calcium in the water. We ordinarily consider that base-exchange processes are stoichiometric, and the line of best fit in Figure 3 would be expected to be at 45°, from which it departs slightly. The author states that the soil or rock-material was presumably calcium saturated prior to contamination by sea-water. The argument would have been clinched more firmly if this had been shown by analysis and if an analysis of the sea-water and a sample calculation were included. To my mind Mr. LOVE'S explanation of the deviations in analyses is correct and his arguments and data are convincing.

SPATIALLY VARIABLE DISCHARGE OVER A SLOPING PLANE

G. H. Keulegan

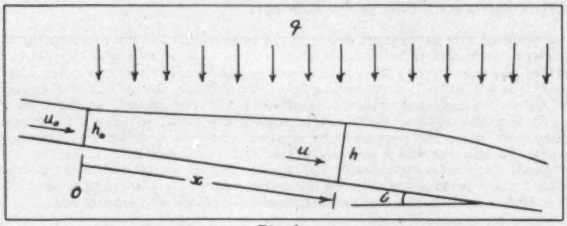

Fig. 1

The equation of motion of a spatially variable discharge in an open channel, the flow being produced by a lateral or a vertical inflow, has been treated previously [see 1, 2 of "References" at end of paper]. These treatments, however, are not immediately applicable to the phenomenon of runoff from a plane surface, which is an example of spatially variable discharge. The following reasons may be mentioned. First, these derivations ignore the effect of a variation of the depth of water with time and also the effect of an initial flow having the same direction as the main current of the plane of runoff. Second, the forms of the final results do not allow a comparison between the frictional effects arising from the solid surface and from the mixing of the added flows. Third, the energy-equation is not adduced. Approximate solutions of the problem of runoff that are practical can be readily obtained from the energy-equation after making due allowance for the relative importance of the resistances arising from the two sources just mentioned. In the derivation to be given these different aspects of the analysis will be developed.

Let positive x coordinate be chosen in the direction of the main current over the plane (see Fig. 1). Denote by h_0 and u_0 the depth of water and the mean velocity, respectively, at the origin of x. Denote by h and u the corresponding quantities at the point x, x>0. Denote the intensity of rain, that is the volume of rainfall over unit-area per unit-time, by q. Obviously q has the dimensions of velocity. The principle of the conservation of mass yields the relation

$$uh = \int_0^x q\,dx - \int_0^x (\partial h/\partial t)\,dx + u_0 h_0 \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

which may be spoken of as the condition of continuity of a spatially variable discharge. If the flow is steady, that is if h is independent of time,

$$uh = \int_0^x q\,dx + u_0 h_0 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

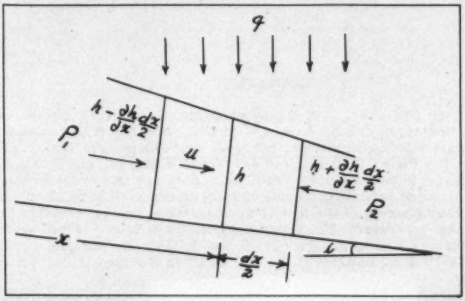

Fig. 2

In addition, if q is constant

$$uh = qx + u_0h_0 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

To establish the dynamical equation of motion, EULER'S well-known method may be used (see Fig. 2). Select in the vicinity of x two sections of unit width, S_1 and S_2, with the coordinate points $[x - (1/2)dx]$ and $[x + (1/2)dx]$, respectively. The body of liquid limited by the sections is subjected to a number of forces all of which are to be resolved in the direction of x positive. Since i is a small angle, the gravitational force has the value $i\rho ghdx$, where ρ is the density of liquid and g the acceleration of gravity. Suppose that the curvature of the water-surface is small. The filaments of liquid are then nearly linear and the pressure within the liquid is nearly hydrostatic. Ignoring the atmospheric pressure, the forces on the sections S_1 and S_2 due to pressure are

$$P_1 = (1/2)\rho g[h-(1/2)(\partial h/\partial x)\,dx]^2$$

and

$$P_2 = (1/2)\rho g[h + (1/2)(\partial h/\partial x)\,dx]^2$$

Their resultant is $-\rho gh(\partial h/\partial x)\,dx$. First denoting the frictional stress of the solid bottom by τ, and next introducing the law of friction

$$\tau = (1/2)\lambda\rho u^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

where λ is the coefficient of friction, the frictional force may be expressed by $-(1/2)\lambda\rho u^2dx$. The mass of the rain entering into the portion of liquid limited by the sections S_1 and S_2 per unit-time is ρqdx. The inclination of the plane being small, the descending rain brings no momentum in the direction of x. The mass of the descending rain after mixing with the main current leaves the section S_2 with the velocity u. The resultant reaction has the value $-\rho qudx$. Ignoring the small effects of the velocity-distribution in a cross-section, the acceleration of the liquid is (du/dt). The kinetic reaction is $\rho h(du/dt)dx$. Writing first the equation that gives the equilibrium of forces in the direction of x positive and then dividing by ρhdx there results $(du/dt) = g[i-(\partial h/\partial x)]-(\lambda/2)(u^2/h)-(qu/h)$. Introducing the expression of acceleration in terms of the local rates, $(du/dt) = (\partial u/\partial t) + u(\partial u/\partial x)$, the above equation becomes

$$[(\partial u/\partial t) + u(\partial u/\partial x)] = g[i-(\partial h/\partial x)]-(\lambda/2)(u^2/h)-(qu/h) \quad \ldots\ldots\ldots\ldots (5)$$

This is the most general form of the dynamic equation of motion for a spatially variable discharge.

When equation (5) is compared with the ordinary equation of motion for flow in open channels [3, p. 477], two differences will be noticed. First, a new term, $-(qu/h)$ is added. This term represents the frictional effect due to mixing of the additive masses of the descending rain with the moving current. It may now be seen that the effect of the mixing is equivalent to an apparent stress of value $-(\rho qu)$ which is applied to the upper surface of water. The structure of the term is the same as the structure of a REYNOLDS stress. Second, the coefficients of velocity-distribution, which arise necessarily in a rigorous derivation, are missing. In a rigorous derivation the terms $[u(\partial u/\partial x)]$ and (qu/h) are multiplied by the dimensionless coefficients α and β, respectively. A few remarks concerning α and β are desirable. The value of α is larger for the laminar regime than for the turbulent. In the laminar regime it is effected by the intensity of rain q. The variations that are to be expected fall within the extreme limits of 1.20 and 1.33. No specific limits can be given for β. If the depth of water is small and the length of the wetted plane is large, the resistance due to the mass-mixing of the rain is small in comparison with the resistance of the solid bottom as will be shown presently. In that case the exact value of β is immaterial and may be taken as unity. If on the contrary the depth of water is large and the length of plane small, as for example, in a side-spillway channel of short length, the friction on the bottom is negligible, the velocity-distribution in the core is practically uniform, and therefore β is nearly unity.

The analytical solution of the problem of runoff must now result from the dynamical equation, equation (5), from the law of resistance, equation (4), and from the equation of continuity, equation (1). The mathematical difficulties of this solution, however, are considerable and therefore it is desirable to resort to approximate solutions. It is conceivable that the derivation of an approximate but practical formula will be facilitated if some of the terms of equation (5) can be neglected. Consider first the ratio of the two resistance-terms of this same equation. This ratio is $(2q/\lambda u)$ which in view of equation (3) becomes $(2h/\lambda x)[1-(u_0/u)(h_0/h)]$. Accordingly, the term containing q may be

discarded if

$$(2h/x) << \lambda \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

Experience shows that with increasing REYNOLDS number λ approaches a limiting value. Furthermore if the length of the plane of runoff is very large, as is usually the case, the variation of h with distance is small. Thus, in the case of steady runoff over large lengths with q constant, it is justifiable to dispense with the friction-term involving q, except in the initial stretches of the plane of runoff.

To weigh the importance of the depth and kinetic-energy terms it is sufficient to consider the case of steady flow. However, to simplify the required comparisons of terms it is desirable to obtain the energy-equation appropriate to the problem. Multiplying both sides of equation (5) by uh, integrating the resulting equation with respect to x, and making use of equation (2) gives

$$uh[(u^2/2) + gh] = gix \int_0^x qdx + \int_0^x [gqh - giqx - (1/2)qu^2 - (1/2)\lambda u^3]dx + u_0h_0[u_0^2/2 + gh_0] + giu_0h_0 \quad (7)$$

which is the desired energy-equation, with the quantities of the left-hand member referring to the point x. Assuming that q is constant and u_o vanishes and

$$x(u^2 + 2gh) = gix^2 + 2\int_0^x ghdx - \int_0^x u^2dx - (1/q) \int_0^x \lambda u^3dx \quad \ldots\ldots\ldots (8)$$

Assume that the inequalities

$$u^2 << gix \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (9)$$

$$2h << ix \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (10)$$

are satisfied for large values of x and the length of the plane of runoff is large. Then equation (8) simplifies to

$$gix^2 = (1/q) \int_0^x \lambda u^3dx \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (11)$$

It is necessary to examine the inequality (9). Differentiating equation (11) with respect to x and using equation (3)

$$(u^2/gix) = (2/\lambda)(h/x) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (12)$$

Accordingly, in the case that the inequalities (6) and (10) are satisfied, the inequality (9) is also satisfied. Under these conditions equation (11) may be taken as the starting point for the approximate solution of the problem of the runoff.

The method for obtaining these approximate solutions will not be discussed here in detail. But, before such solutions are attempted it is necessary that the dependence of λ on the REYNOLDS number, (uh/ν), be ascertained by experiments. Even though the direct resistive effect of the falling rain is small, the perturbing effect of g on λ may be appreciable, since falling rain accentuates the velocity-gradient near the bottom. From equation (5)

$$(\lambda/2) = [1 - (dh/dx)](gh/u^2) - (du/dx)(h/u) - (q/u) \quad \ldots\ldots\ldots\ldots (13)$$

which is the desired relation to determine λ after the dependence of u or of h on x is established by experimental observations.

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[2] K. HILDING BEIJ, Flow in roof gutters, J. Res. Nation. Bur. Stand., v. 12, p. 193, 1934.
[3] G. H. KEULEGAN and G. W. PATTERSON, Effect of turbulence and channel slope on translation waves, J. Res. Nation. Bur. Stand., v. 30, p. 461, 1943.

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DISCUSSION

WILLIAM S. EISENLOHR, Jr. (Arlington, Virginia)--Dr. KEULEGAN has presented a very interesting paper. It is especially appealing to the writer because he is of the opinion that the rational method of analysis used by the author should be used more widely in the solution of hydraulic problems. The method of setting up a diagram of forces, and deducing therefrom the equation of flow, does much to remove the solution of hydraulic problems from the field of pure empiricism. It also affords a sound basis for judging the validity of simplifying approximations which are an important part of this paper.

The author has titled his paper spatially variable flow, and then proceeds to develop his equations using time as a variable, also. To the writer it seems much simpler, once having postulated a flow which is steady with respect to time, and which is necessary for equilibrium-conditions, to write the equation of momentum change per unit-time using total differentials with respect to x in much the same manner as was used for a somewhat related problem [WM. S. EISENLOHR, Jr., Coefficients for velocity distribution in open-channel flow: Proc. Amer. Soc. Civ. Eng., pp. 15-26, January, 1944].

The forces in the author's derivation remain unchanged, except for the use of the total differential, but the kinetic reaction must now be expressed in terms of x, $\rho h dx \left\{[u + (du/dx)(dx/2)]^2 - [u - (du/dx)(dx/2)]\right\}/2dx = hudu$. Equating this term to the forces involved gives the equation

$$hu\,du = i\rho g h\,dx - \rho g h\,(dh/dx)\,dx - (\lambda/2)\,\rho u^2 dx - \rho q u\,dx \quad \ldots\ldots\ldots\ldots (1)$$

Dividing by $\rho h dx$ as did the author gives his equation (5) with $(\partial u/\partial t) = 0$.

$$u\,(du/dx) = g[1-(dh/dx)] - (\lambda/2)(u^2/h) - (q^u/h) \quad \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

If the author desires to make his equation (5) perfectly general, it would seem that it would be necessary to include a term for lateral or vertical outflow. In the problem of runoff over a sloping ground-surface as a result of rain, the vertical outflow would be equal to the infiltration-rate. Letting the velocity of infiltration be I the mass of water leaving the portion of the liquid between sections S_1 and S_2 per unit-time is $(\rho I dx)$. This mass of water before leaving the main current had a velocity u. The resulting reaction has the value $(\rho I u dx)$. This can be inserted as an additional term in equation (1) of this discussion, or it can be considered as being included in the term $(\rho q_n u dx)$, provided it is understood that q_n is the net velocity of inflow being the rainfall rate minus the infiltration rate. The inclusion of vertical or lateral outflow presumably would have no effect on the validity of the author's final equation, but under certain conditions would have considerable effect on the application of the equation.

THE SURFACE-PROFILE OF OVERLAND FLOW

C. F. Izzard

This paper presents experimental data applying the equation of motion mathematically derived by KEULEGAN in his paper entitled "Spatially variable discharge over a sloping plane" [see 1 of "References" at end of paper]. The experimental data are taken from a cooperative research-project of the Public Roads Administration and the Soil Conservation Service and are based on run-off from simulated rainfall as described in a previous paper [2]. The paved surface on which the principal data reported (Series II) were obtained was a commercial slate roofing-felt impregnated with asphalt and firmly cemented to the smooth sand-asphalt surface (Series I) used for earlier tests [2]. Subsequently this surface was covered by blue-grass sod (Series III) carefully selected for uniformity, with soil of average thickness about 1-1/4 inches. Thin wooden strips were nailed to the floor to retard movement of water beneath the sod.

This paper is limited to consideration of flow at equilibrium during rainfall at constant rate and does not involve flow on the rising or falling limbs of the hydrograph except for some data based on the recession-curve at the point where discharge is equal to the discharge during rainfall at equilibrium as will be discussed subsequently.

The equation of motion for spatially variable discharge as derived by KEULEGAN using nomenclature conforming essentially to the American Standard Letter Symbols for Hydraulics [3] is, for the equilibrium conditions

$$V\,(dV/d\ell) = g[S_0 - (dy/d\ell)] - (\lambda/2)(V^2/y) - (V^2/\ell) \quad \ldots\ldots\ldots\ldots (1)$$

in which the symbols (and others used subsequently) have the following definitions: V = mean velocity in cross-section, feet per second; y = depth of flow, feet; ℓ = distance from upper end of the plot, feet; L = total length of plot, feet; S_0 = slope of plot (nondimensional); g = acceleration of gravity = 32.2 feet per second^2; λ = resistance-coefficient (nondimensional); i = rainfall-intensity, inches per hour or cubic feet per second per acre; D_e = detention on unit-strip at equilibrium, feet^3; D_ℓ = detention on unit-strip when discharge = q_e on recession-hydrograph; q_e = discharge at point ℓ feet from upper end of unit-strip at equilibrium, feet^2 per second; F = FROUDE number = (V^2/gy); R = REYNOLDS number; K = detention-coefficient = $(D_e/q_e^{1/3}$, feet$^2 \times$ seconds$^{1/3}$; and k = depth-coefficient = $(y/\ell)^{1/3}$, feet$^{2/3}$.

The equilibrium-condition is defined by the equation

$$q_e = V_y = (i\ell/43200) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

The resistance-coefficient λ is identical with that used by KEULEGAN

$$\tau = (1/2)\lambda\rho V^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

wherein τ is the mean intensity of the shearing force at surface of the plot and ρ is the density of the water. It will be shown later that the magnitude of the resistance-coefficient is affected by the disturbance of flow caused by the raindrops. This might be visualized as a relative roughness-effect imposed from above on the flow in addition to the relative roughness of the surface on which the water is flowing.

The experimental data show that for a rainfall-intensity up to about 3.8 inches per hour and for lengths of overland flow up to 72 feet the average depth of flow at equilibrium is proportional to the cube root of the discharge at the end of the plot, and inversely proportional to the cube root of the slope of the plot for slopes from 0.001 minimum to 0.04 maximum. This is true for the paved surface, as shown in Figure 1, and for the turfed surface (slopes from 0.01 to 0.04), as shown in Figure 2. The average depth was determined from the total volume of detention divided by the area of the plot, detention at equilibrium being the difference between mass-rainfall and mass-runoff. In the case of the turfed plot, the computed average depth is less than the true average depth, if that could be measured, because of the volume of grass-crowns and other matter within the flow-prism. It was not considered feasible to measure accurately the elevation of the water-surface continually disturbed by impact of raindrops.

Some infiltration occurred on the turfed plot despite the impermeable sub-grade and the apparently saturated condition of the 1-1/4 inches of soil. Adjustments in detention were made by means of a logarithmic extension of the recession-hydrograph from each previous run. The data as presented in Figure 2 are believed to represent a reasonably uniform condition of saturation in the soil. The hydraulic effect of the turf did not change materially throughout the tests since the nineteenth and last run made under identical conditions to the first run reproduced the hydrograph of the latter very closely.

All detention-data in Figure 1 have been reduced to a common temperature of 60°F because it was discovered that resistance to flow was inversely proportional to REYNOLDS number. The measured detention was corrected in inverse proportion to the dynamic viscosity, neglecting density which varied very little for the 52°F to 82°F range of temperature of the runoff-water. No correction for temperature was made on turf-runs since accuracy of the computed detention as adjusted for infiltration did not warrant such refinement, and furthermore the temperature-range was small.

In an attempt to determine the resistance-coefficient for the paved surface on the recession-flow when rainfall-disturbance was absent, detention was also computed at the instant at which the rate of discharge was equal to the equilibrium-discharge during rainfall. As has previously been demonstrated on paved plots, there is a momentary increase in discharge after rainfall ceases due to the removal of the resistance created by the rainfall-disturbance [2]. Since discharge was changing rapidly with time at this instant, true equilibrium as defined by equation (2) did not exist, but despite this fact the resistance-coefficient so determined checks rather closely with that determined with steady uniform flow (admitted at the upper end of the plot) as shown in Figure 5 and discussed subsequently. Figure 1 shows the relationship of average depth to discharge on the paved plot at the instant where discharge on the recession-curve was equal to the equilibrium-discharge. It will be noted that the proportionality constant for the detention following a rainfall of 3.6 ± inches per hour is identical to that following the rainfall of 1.8 ± inches per hour as would be expected.

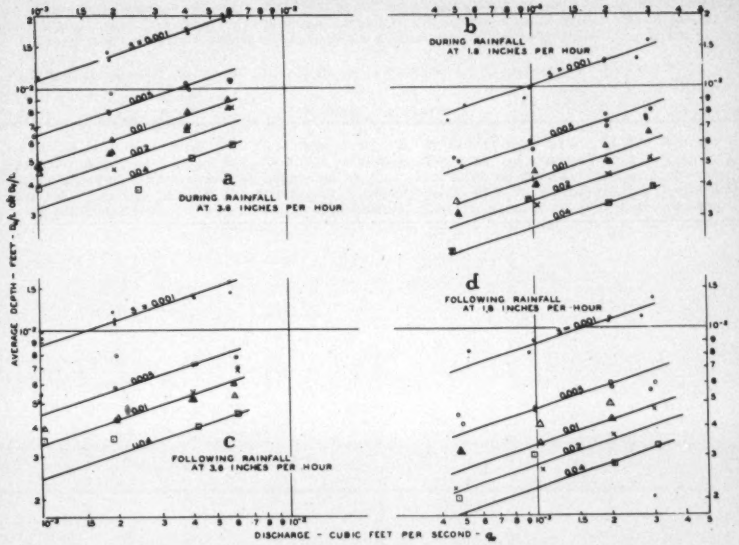

Fig. 1--Average depth as function of equilibrium-rate of discharge on paved plot (Series II)

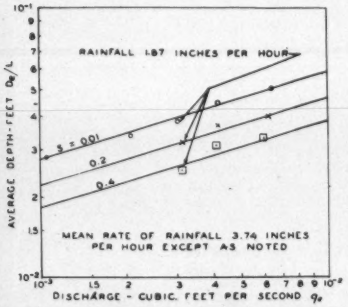

Fig. 2--Average depth as function of equilibrium-rate of discharge on turfed plot (Series III)

The general equation for average depth is

$$(D_e/L) = K\,(q_e)^{1/3} \quad \ldots\ldots\ldots (4)$$

The coefficient K is inversely proportional to the cube root of the slope as shown in Figure 3. This coefficient also involves the resistance-coefficient λ, which in turn is a function of the rainfall-intensity as well as the surface-roughness.

In order to evaluate the resistance-coefficient λ equation (1) was transformed as follows

$$\lambda = (2k/\ell)\,(k^2\ell^2/q_e^2)\,g[S_0 - (k/3\ell^{2/3})] - (5/3)\ell^{1/3} \quad \ldots\ldots\ldots (5)$$

in which k is defined by the equation

$$y = k\ell^{1/3} \quad \ldots\ldots\ldots (6)$$

This equation is derived from equation (4) by differentiation as can be checked by integrating the expression

$$D_e = \int_0^L y\,d\ell = \int_0^L k\ell^{1/3}\,d\ell$$

which gives

$$(D_e/L) = (3/4)\,kL^{1/3} \quad \ldots\ldots\ldots (7)$$

and indicates that the average depth is three-fourths of the depth at L. The approximate validity of this statement will be shown subsequently by comparison of profiles computed from the equation of motion in a modified form and the approximate surface-profile equation given in equation (6).

From the equilibrium-equation (2) the detention-coefficient K is related to the depth coefficient k as follows

$$k = (4/3)\ K\ (1/43200)^{1/3} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (8)$$

Values of λ computed from equation (5) are plotted against REYNOLDS number R for values of K derived from Figures 1 and 2 for both surfaces in Figure 4. For the entire range of the data on both paved and turfed surfaces the product (λ R) is approximately constant for a given rainfall-intensity on a given surface. For the flatter slopes, particularly $S_0 = 0.001$, the data vary appreciably from values of (λ R) on steeper slopes, probably because equation (6), used in computing k, does not truly represent the actual surface-profile under those conditions.

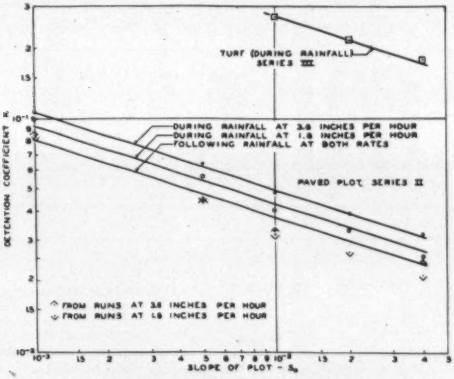
TURF (DURING RAINFALL) SERIES III
DURING RAINFALL AT 3.8 INCHES PER HOUR
DURING RAINFALL AT 1.8 INCHES PER HOUR
FOLLOWING RAINFALL AT BOTH RATES
PAVED PLOT, SERIES II
FROM RUNS AT 3.8 INCHES PER HOUR
FROM RUNS AT 1.8 INCHES PER HOUR
DETENTION COEFFICIENT K
SLOPE OF PLOT - S_0

Fig. 3--Detention-coefficient as function of slope of plot for paved and turfed surfaces (Series II and III)

The logarithm of (λ R) has been plotted against rainfall intensity in Figure 6. For comparative purposes data derived from the first series of experiments on a smooth sand-asphalt plot [2] are also shown but they are subject to revision when refinements in methods developed in the second series here reported have been made.

A tentative equation fitting the data for the rougher paved plot (Series II) is

$$(\lambda R) = 27\ (0.21\ i^{4/3} + 1) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (9)$$

It will be observed that when i = 0, (λR) = 27, thus corresponding to the derivation shown in Figure 4 for the recession-phase.

This value of (λ R) closely corresponds with rough data plotted in Figure 5 obtained from actual measurement of depth of flow for various rates of discharge in tests in which steady uniform flow was approximated. These tests were performed by admitting water at the upper end of the plot over a series of stilling-pools so that about 50 feet of length was available to establish normal flow at the cross-section at which depth was measured with two point gages at the quarter-points of the six-foot width.

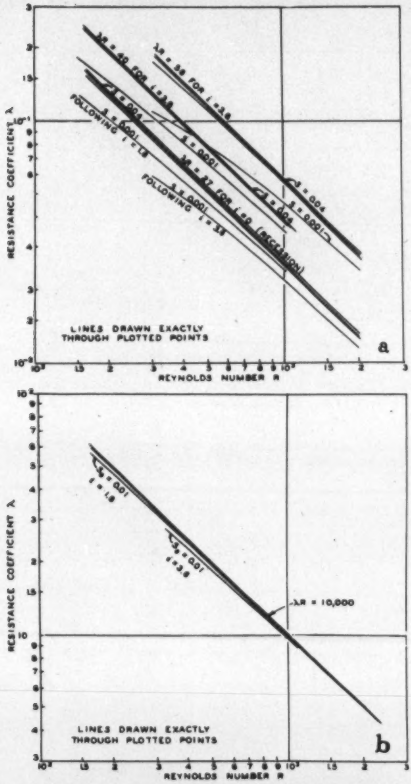

Fig. 4--Resistance-coefficient as function of Reynolds number; (a) paved plot (Series II); (b) turf (Series III)

Figure 5 also indicates that the viscous-flow state, which appears to exist below R = 1,000, enters a transition-stage at that point and that a turbulent phase may begin at about R = 4,000. The data unfortunately do not extend far enough into the latter phase to warrant any conclusions. The limiting value of R = 2,000 in the rainfall-tests is still in the transition-region. It appears reasonable to surmise, therefore, that for rainfall-tests of greater intensity on 72-foot plots, or for overland flow of the same intensity (3.8 inches per hour) on longer plots, a change in type of flow will occur for the recession-flow and also for flow disturbed by raindrop-impact. Consequently use of the equations to extrapolate beyond the limits of the data is not advisable.

Examination of the computations for λ based on equation (5) shows that the term $(5/3)g^{1/3}$ is of negligible importance except on very flat slopes (0.001). This term corresponds to the acceleration-term plus the raindrop-momentum term (first and last terms, respectively) in equation (1).

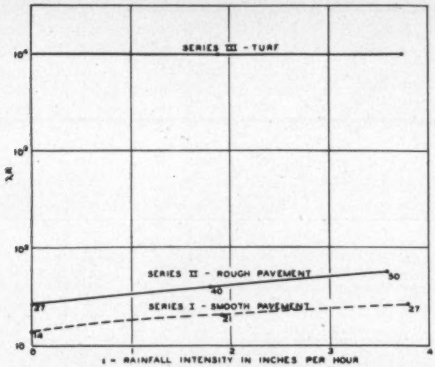

Fig. 5--Resistance-coefficient as function of Reynolds number for steady uniform flow on paved surface: Series II

Consequently it may be said that for approximate purposes on slopes steeper than 0.005 the force necessary to accelerate flow between sections and to impart velocity to raindrops in the direction of flow may be neglected.

Eliminating only the raindrop-momentum (last term) in equation (1) and expressing rates in the increment-form

$$V\,(\Delta V/\Delta \ell) = g[S_0 - (\Delta y/\Delta \ell)] - (\lambda/2)(V^2/y) \quad \ldots\ldots\ldots\ldots\ldots\ldots (10)$$

The increment in velocity ΔV between two sections $\Delta \ell$ apart, y being the depth at a point midway between the sections is

$$\Delta V = \left\{V[(\Delta \ell/\ell) - (\Delta y/y)]\right\}/[1-(\Delta y/2y)^2]$$

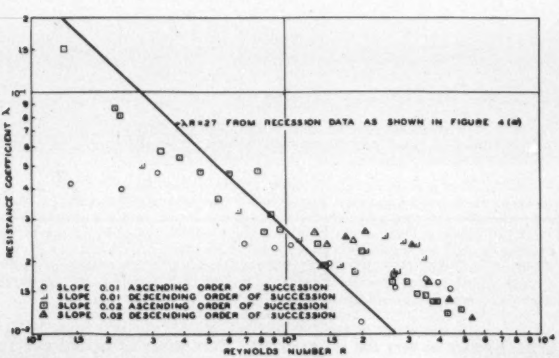
RESISTANCE COEFFICIENT λ
λR=27 FROM RECESSION DATA AS SHOWN IN FIGURE 4(a)
SLOPE 0.01 ASCENDING ORDER OF SUCCESSION
SLOPE 0.01 DESCENDING ORDER OF SUCCESSION
SLOPE 0.02 ASCENDING ORDER OF SUCCESSION
SLOPE 0.02 DESCENDING ORDER OF SUCCESSION
REYNOLDS NUMBER R

Fig. 6--Product λR as function of rainfall-intensity for the three types of surface tested

Dropping out the second-order term in the denominator, substituting the resulting equivalent for ΔV in equation (10) and using the FROUDE number $F = (V^2/gy)$ results in the equation (11).

$$(\Delta y/\Delta \ell) = \left\{S_0 - (F/\ell)[(\lambda \ell/2) + y]\right\}/(1-F) \quad \ldots\ldots\ldots\ldots\ldots\ldots (11)$$

This is the dimensionally correct equation for equilibrium-surface profile taking into consideration the varying discharge along the plot, the slope of the water-surface relative to the bed of the plot, the slope of the plot, and the resistance to flow as a function of rainfall-intensity, temperature of water, and roughness of plot-surface. The equation has been used to compute profiles for typical runs as shown in Figures 7 and 8. The average variation between detention computed from these profiles and the measured detention as adjusted for temperature and rainfall-intensity, as shown in Table 1, is 4.9 per cent.

By inspection this equation (11) shows: (a) That slope of the surface-profile is level at the upper end of the plot; (b) that slope of water-surface relative to plot is positive (depth increasing)

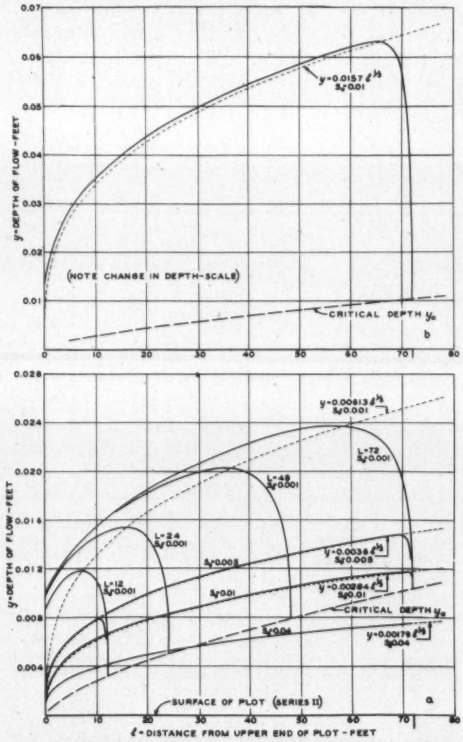

Fig. 7--Surface profiles computed by equation (11); (a) paved plot (Series II) and (b) turfed plot (Series III)

Table 1--Comparison of actual and computed volumes of detention on typical paved and turfed plots at equilibrium

Run No.	Slope of plot, S_0	Length of plot, L	Rainfall intensity, i	Temperature	Actual detention, D_e	Actual detention adjusted,[a] D_e'	Computed detention	Variation[b]
		Feet	Inches per hour	°F	Sq ft	Sq ft	Sq ft	Per cent
101	.001	72	3.45	56	1.46	1.46	1.43	-2.1
103	.001	72	3.48	56	1.39	1.39	1.43	+2.9
104	.001	72	3.63	64	1.41	1.44	1.43	-0.7
106	.001	48	3.67	57	0.855	0.832	0.834	+0.2
107	.001	48	3.73	52	0.835	0.789	0.834	+5.7
110	.001	24	3.49	62	0.336	0.346	0.339	-2.0
111	.001	24	3.55	62	0.314	0.320	0.339	+5.9
114	.001	24	3.56	63	0.319	0.329	0.339	+3.0
115	.001	12	3.65	64	0.125	0.126	0.127	+0.8
118	.001	12	3.65	65	0.129	0.130	0.127	-2.3
131	.005	72	3.66	67	0.747	0.765	0.814	+6.4
132	.005	72	3.63	72	0.750	0.790	0.814	+3.0
133	.005	72	3.67	73	0.727	0.762	0.814	+6.8
119	.005	12	3.52	60	0.0820	0.083	0.075	-9.6
120	.005	12	3.52	58	0.0763	0.076	0.075	-1.3
121	.005	12	3.58	58	0.0835	0.082	0.075	-8.5
173	.04	72	3.68	68	0.394	0.401	0.404	+0.7
167	.04	12	3.66	66	0.0463	0.047	0.037	-21.3
301[c]	.01	72	3.81	78	3.70	3.92	3.58	-8.7

[a]Adjusted to 60°F and intensity 3.6 inches per hour. [b](Computed detention/actual detention adjusted) × 100. [c]Bluegrass-turf; all other runs on paved surface (Series II).

so long as $(F/\ell)[(\lambda \ell/2) + y] < S_0$; (c) beyond point established by equality in (b) above, slope is negative and depth decreases, therefore, depth is a maximum at such point and also $(\Delta y/\Delta \ell) = 0$, and therefore

$$y = (\lambda/2)(V^2/2g) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (12)$$

which is the locus of the point of maximum depth for various lengths of plot on a given slope.

Mathematically equation (11) cannot be integrated by any simple method, although it is probable that functions similar to BRESSE'S backwater tables may be derived, if needed. The computed profiles were obtained by trial and error using equation (11) solved for $\Delta \ell$ and starting from a known control, as the critical depth at the point of free overfall, or critical depth relative to the top of an obstruction across the flow as shown in Figure 8.

Figure 8 indicates that the normal surface-profile is affected for only a relatively short distance upstream from the 1/4-inch high dam in that Figure. One run was actually made with such an obstruction modeled from clay. This Figure indicates the possibility of using equation (11) to compute the surface-profile for flow off a paved strip subject to backwater-effect from flow on a turfed shoulder.

Figure 7 also shows profiles plotted from equation (6) using experimental values of k. Note that these profiles intersect the profiles computed from equation (11) at the point of maximum depth, which indicates that equations (6) and (12) give identical results. Examination of the

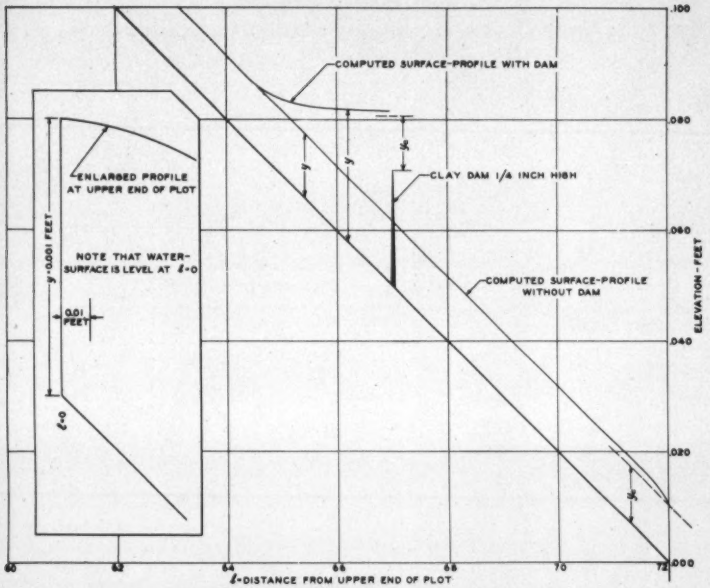

Fig. 8--Surface-profiles computed by equation (11) for paved plot having $S_0 = 0.01$ with 1/4-inch dam five feet from lower end of plot (Series II)

Fig. 9--Rainfall at 3.7 in/hr on turfed plot

Fig. 10--Paved surface used in Series II

Fig. 11--Blue-grass turf used in Series III

variations between this simplified profile-equation and that computed by equation (11) discloses that the areas under the curves are approximately equal, the increased area upstream from the point of intersection being offset by the decreased area downstream from that point. The close coincidence of these curves discloses why the simplified profile-equation (6) fits the experimental data so well, despite the correct observation by HORNER in his discussion of a previous paper [2] that the depth cannot be zero at the upper end of the plot. For practical purposes, equation (6) may be used instead of equation (11) with little error, so long as flow is unobstructed and the equation is not applied to cases where the product (iL) does not exceed 280, more or less. As previously stated there is good reason to believe that flow changes beyond that range in such manner that depth is no longer proportional to the cube root of the discharge.

These computed profiles also indicate that the upper end of the surface-profile is approximately the same regardless of the length of overland flow. This fact justifies the use of detention-data for various lengths of plot to arrive at detention-discharge relationships.

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EFFECT OF REMOVAL OF FOREST VEGETATION UPON WATER-YIELDS

M. D. Hoover

Despite the interest that has been taken in the effect of forest-cover upon stream-flow yields only two experiments [see 1, 2 of "References" at end of paper] have been reported in which stream-flow was measured for the same watershed before and after removal of forest. Both studies were made in western United States in regions of low rainfall.

The present report describes the methods and preliminary results of a similar study made in a region of abundant rainfall in the southern Appalachian Mountains.

The location of the experimental watersheds is the Coweeta Experimental Forest, a field-laboratory of the Appalachian Forest Experiment Station. It is situated in the Nantahala Range of the southern Appalachian Mountains near Franklin, North Carolina. This region is in the zone of maximum precipitation in the eastern United States. Rainfall is distributed uniformly throughout the year. The climate is classed by THORNTHWAITE [3] as superhumid. The mean annual temperature is 55°F and the growing season extends from April 15 to October 15 with a mean temperature of 65°. Winters are comparatively mild. Only about two inches of precipitation occur as snow. Natural vegetation is composed of deciduous trees with abundant shrubs and minor vegetation. Because of the favorable climate plant-growth is rapid and but rarely checked by summer droughts.

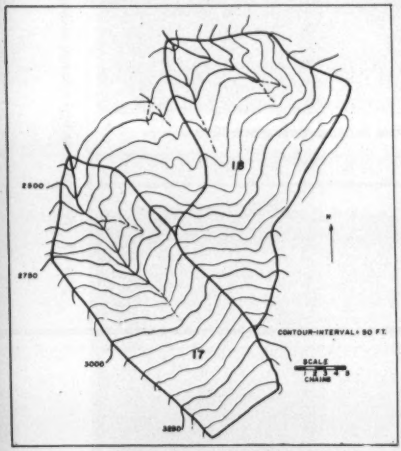

Fig. 1--Drainage-areas 17 and 18, Coweeta Experimental Forest

Under these conditions, vegetation has a maximum opportunity for transpiration. Soil-moisture seldom reaches the wilting-point and does not become a limiting factor for growth of established plants. Evaporation-rates are moderately high. The average evaporation from a standard pan is 35 inches a year.

The plan of this experiment was to compare water-yield for a watershed before and after removal of forest. Before cutting, sufficient stream-flow and climatic records were to be obtained so that the normal relationship between rainfall and runoff could be established. In addition, another similar drainage-area was to be left uncut to serve as a control. After the primary cutting all sprout-growth on the treated watershed was to be cut back for five growing seasons. In order to isolate the effect of transpiration, it was necessary to carry out the treatment so that a minimum change in infiltration-capacity would be caused. This required that the litter-and-humus layer should be disturbed as little as possible by the cutting of the trees.

After consideration of the 30 watersheds on the Coweeta Forest, two adjacent drainage-areas were found that were suitable for this investigation. They are designated as Area Nos. 17 and 18. These two watersheds are essentially similar and receive almost identical rainfall. The area of No. 17 is 32.8 acres and of No. 18, 30.8 acres. Figure 1 is a contour-map of these watersheds.

The underlying rock-formation of both watersheds is the Carolina Gneiss of Pre-Cambrian origin. The most common rocks are mica-gneiss and mica-schist. The feldspar of these rocks weathers rapidly and forms a clay-soil with fragments of schist, quartz, and mica. The surface-soil is a red-brown loam and the subsoil is a micaceous silty clay. Rock-fragments are abundant throughout the profile. The average soil-depth is greater than four feet and the soil is underlain by soft disintegrated rock.

Fig. 2--Drainage-Area 17 before cutting, December 1940

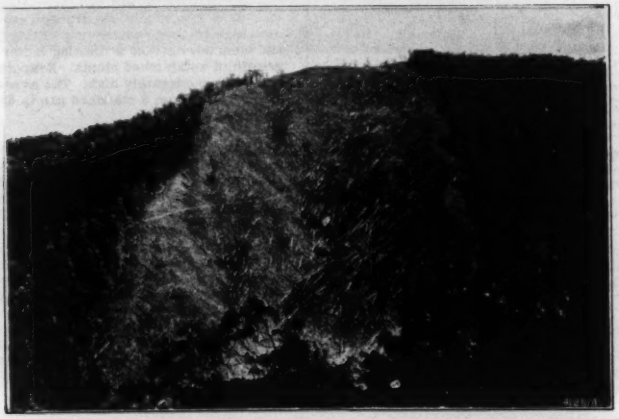

Fig. 3--Drainage-Area 17 after cutting of all woody vegetation, July 1941
(note isolation strip cut around watershed-boundary)

The watershed-boundaries are defined by sharp ridges and there is no indication of any quantity of seepage escaping measurement. Stream-flow is measured by sharp crested V-notch weirs set in concrete cut-off walls. Continuous records began in June, 1936.

Area No. 17 was selected for cutting with No. 18 to serve as a control. The forest stand on No. 17 was typical of the upper-slope type in the southern Appalachians (Fig. 2). The principal tree-species were chestnut oak, hickory, red maple, black oak, eastern red oak, and black tupelo. Associated species included black locust, sourwood, flowering dogwood, and sassafras.

Table 1.--Monthly precipitation and runoff areas 17 and 18

Year, item	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Year
1936-37, Rainfall	2.06	12.18	12.87	6.54	3.10	7.97	2.32	5.70	4.05	4.83	2.93	9.53	74.08
Runoff No. 18	1.16	3.07	10.03	6.63	4.32	4.14	3.47	2.00	1.26	1.00	0.75	1.24	39.07
No. 17	0.74	2.58	9.39	5.77	3.45	3.37	2.97	1.46	0.78	0.55	0.42	0.86	32.34
1937-38, Rainfall	3.07	6.07	4.83	2.92	9.04	6.28	6.50	6.99	11.96	3.59	3.84	0.15	65.25
Runoff No. 18	0.91	1.65	2.22	1.96	4.11	5.19	3.12	2.58	3.22	3.31	1.80	1.16	31.23
No. 17	0.58	1.33	1.89	1.64	3.43	4.47	2.35	1.99	2.68	2.83	1.42	0.79	25.40
1938-39, Rainfall	11.77	3.45	8.24	16.76	8.67	5.54	3.89	3.48	5.90	6.96	1.19	0.90	76.75
Runoff No. 18	2.38	1.88	3.12	12.75	9.91	5.37	3.57	2.05	1.53	1.29	0.69	0.55	45.07
No. 17	1.95	1.59	2.70	10.98	8.23	4.21	2.84	1.56	1.06	0.91	0.48	0.39	36.89
1939-40, Rainfall	0.88	4.30	4.03	7.84	6.13	7.70	2.03	7.82	4.53	14.30	0.96	1.94	62.46
Runoff No. 18	0.42	0.53	0.70	1.72	1.97	3.90	2.96	2.18	1.45	2.24	1.83	1.33	21.12
No. 17	0.31	0.36	0.47	1.14	1.42	3.23	2.43	1.79	1.13	2.02	1.67	0.97	16.93
1940-41, Rainfall	6.34	5.65	3.89	1.60	5.43	3.47	1.32	3.19	10.80	2.92	3.48	3.27	51.36
Runoff No. 18	1.36	1.47	2.09	1.67	2.29	2.67	1.74	1.08	1.85	0.83	0.54	0.45	17.84
No. 17	1.06	1.32	1.84	1.49	2.07	2.54	1.86	1.36	4.08	2.19	1.45	1.18	22.44
Increased flow after treatment	Cutting in progress					+0.42	+0.54	+0.61	+2.84	+1.66	+1.17	+0.92	+ 8.16
Area No. 17													
1941-42, Rainfall	3.88	8.11	5.26	6.91	9.75	1.00	10.03	3.23	9.89	4.15	6.26	3.57	72.04
Runoff No. 18	0.59	1.58	2.06	4.29	6.73	3.89	4.10	2.44	2.09	1.48	1.31	1.14	31.70
No. 17	1.81	3.86	4.36	5.21	6.73	3.63	4.23	2.87	2.61	2.58	2.46	2.38	42.63
Increased flow after treatment	+1.43	+2.60	+2.67	+1.54	+0.89	+0.43	+0.85	+0.95	+0.98	+1.48	+1.51	+1.41	+16.74
1942-43, Rainfall	2.97	13.88	7.30	5.89	10.23	6.19	4.61	6.89	12.16	5.24	5.54	2.92	83.83
Runoff No. 18	1.10	4.73	5.79	6.30	6.09	5.10	3.76	2.35	3.61	2.78	1.78	1.27	44.66
No. 17	1.80	5.82	6.75	6.27	5.58	4.48	3.38	2.24	4.42	3.51	2.22	1.46	47.93
Increased flow after treatment	+0.96	+1.76	+1.77	+0.83	+0.33	+0.24	+0.30	+0.39	+1.47	+1.28	+0.86	+0.49	+10.68

Rhododendron and mountainlaurel formed a dense understory on 60 per cent of the area. No forest-fires had occurred for at least 25 years. No logging has been done on this area with the exception of a few trees felled for tanbark in 1917.

All woody vegetation on this watershed was cut between January 6 and March 31, 1941 (Fig. 3). To prevent disturbance to the soil, trees were left where they fell and no material was removed. Tops and limbs were lopped to lay close to the ground and scattered uniformly over the soil-surface. Because of the large proportion of evergreen rhododendron and mountainlaurel, the resulting slash-cover formed a loose mulch over the area. This protected the soil and maintained infiltration-capacity. It also served to protect the soil from drying by Sun and wind, preventing any great increase in evaporation after cutting. An isolation strip 50 feet in width around the watershed-boundary received identical treatment.

Regrowth was vigorous and cutting of all sprouts was carried out in August, 1941. In 1942,

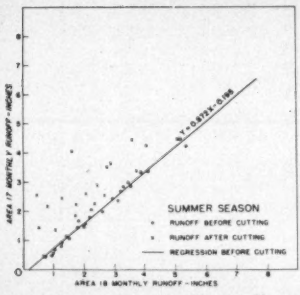

Fig. 4--Linear regression for runoff, areas 17 and 18 before and after cutting Area 17, summer season

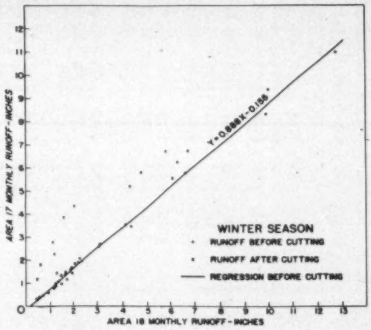

Fig. 5--Linear regression for runoff, areas 17 and 18 before and after cutting Area 17, winter season

sprouting began June 15 and was completed in August. Because of labor shortage it was not possible to cut back sprouts in 1943. At the end of that growing season sprouts had reached heights of ten feet with an average height of five feet. Vegetation was at a minimum during the growing season of 1941 with the primary cutting and a sprouting both occurring in that year. In 1942, because of the longer period during which sprout-cutting took place, vegetation had an opportunity to make considerable growth. With no cutting in 1943, reestablishment of vegetation proceeded rapidly favored by abundant rainfall.

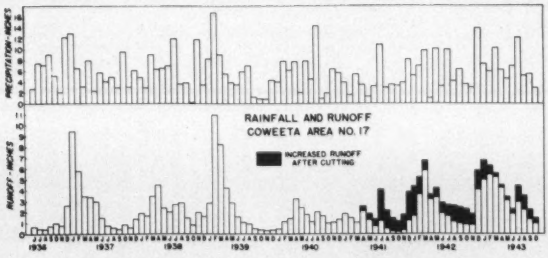

Fig. 6--Precipitation and runoff by months, Area 17

Rainfall and runoff for treated and control watersheds is given by months in Table 1. Previous to the treatment, Area 18 had somewhat higher yield but responded to climatic factors in the same manner as Area 17. The correlation-coefficient for monthly runoff of the two areas was +0.99. By means of linear regression it was possible to predict the monthly runoff of No. 17 from that of No. 18 with a standard error of 0.15 inch. This relationship is indicated by the points marked by small circles in Figures 4 and 5. The establishment of this relation with the two areas in natural forest-cover permits the estimation of the change in water-yield as a result of the treatment. The difference between actual runoff after the cutting and that predicted by the relationship existing before cutting is attributed to the effect of removal of vegetation. For each month after treatment the runoff of Area 17 was in excess of that which would have been expected by its previous relation with Area 18. This difference is given in Table 1 as "increased flow after treatment". Figure 6 is based on this Table and shows graphically the monthly increased runoff and the predicted

stream-flow if Area 17 had not been treated.

Table 1 gives an increased flow for the first six months after cutting of 8.16 inches. For the water-years (November to October) 1941-42 and 1942-43 the indicated increase is 16.74 and 10.68 inches, respectively. The influence of increased soil-moisture resulting from cutting is apparent from consideration of Figure 6. The maximum monthly increase to runoff of 2.84 inches occurred in July, 1941. In this month rainfall was 10.80 inches but preceding rainfall was deficient. Under forested conditions the heavy rainfall in July was barely sufficient to satisfy soil-moisture deficiencies and but little runoff resulted. However, on the treated area, because of the lower drain on soil-moisture, the rains during July made large contributions to ground-water storage resulting in a greatly increased runoff for this and the following months. The normal period of soil-moisture replenishment is in the fall. In both 1941 and 1942 the rapid replenishment of soil-moisture on the treated area resulted in a large increase to runoff during this time.

Early in the winter season soil-moisture deficiencies under natural forest disappear and ground-water recharge occurs. The small differences in runoff after treatment during late winter and early spring indicate that ground-water storage is at a maximum both on treated and untreated watersheds at this time. Under this condition the influence of treatment is largely eliminated.

Because plants obtain water for transpiration from soil-moisture, it is impossible to derive direct values for the reduction in transpiration for individual months. However, by summing the increased stream-flow resulting from cutting beginning and ending with periods of maximum soil-moisture it is possible to obtain the annual amount used in transpiration. At the first of April, in all years of observation, soil-moisture has been at field-capacity. The cumulative increased runoff from April 1 to March 31 was 17.29 inches for 1941-42 and 13.26 inches for 1942-43. The value for the first year was obtained under minimum plant-cover and should approximate the transpiration that would have occurred under natural forest-cover. A lower value occurred in the second year because the sprouts had a longer average opportunity for growth. When the winter records are available for 1943-44, it is expected that transpiration of the undisturbed sprouts will be considerably greater for this year.

The almost complete elimination of transpiration in the first year of treatment provided an opportunity to check the applicability of MEYER'S curves of evaporation which are based on monthly mean temperature and precipitation [4]. Using a coefficient of unity as was done in a previous study on another Coweeta Watershed [5], it was found that evaporation derived from the curves was only 0.16 inch larger than the actual water-loss from the area. Table 2 was constructed to indicate the distribution of water-losses and ground-water storage-changes before and after treatment.

In Table 2, the first three columns are results of actual measurement within the drainage-area. The change in ground-water storage is based on the ground-water-storage curve described by SNYDER [6]. Runoff corrected for storage represents the actual volume of runoff which was the result of rainfall occurring during the given season. The actual water-loss is the difference between this value and the observed rainfall. This water-loss is composed of evaporation, transpiration, and changes in soil-moisture. MEYER'S evaporation-curves include interception by vegetation canopies. To separate interception from evaporation from the soil, Column (8) was included. The values for interception were estimated for individual storms based on actual measurements made in similar vegetation by the Appalachian Forest Experiment Station [7]. After cutting, interception includes evaporation from the brush-mulch. Soil-evaporation is the difference between MEYER'S evaporation and interception. The residual loss after evaporation is given in Column (10) as transpiration ± soil-moisture changes. The value for annual transpiration is the sum of Column (10) for the 12-month period April to March to eliminate variations in soil-moisture.

The evaporation derived by MEYER'S curve apparently applies as well before cutting as it does after treatment. Increase in soil-evaporation after cutting is offset by the decreased interception.

As determined by the relationship with the control-watershed, the increased runoff in the first year--April, 1941, to March, 1942--was 17.29 inches which checks very well with computed transpiration previous to cutting. The increased runoff in the second year plus transpiration of the sprouts was 19.23 inches which also agrees with computed transpiration of forest-cover.

Maximum peak-discharges during storm-periods have not been significantly changed by the treatment. No overland flow has occurred and runoff is still controlled by ground-water conditions.

Table 2--Area No. 17: Seasonal rainfall, runoff, and distribution of water-losses
(All values in area-inches)

Season	Temp. (1) °F	Rain-fall (2)	Run-off (3)	Change in storage (4)	Runoff corr.for storage (5)	Actual water-loss (6)	Evap., Meyer (7)	Inter-cep-tion (8)	Soil evapo-ration (9)	Transp. ± soil-moisture (10)	Annual transp. ending Mar.31 (11)
Oct. 1936-											
Mar. 1937	45.2	41.92	22.88	+2.47	25.35	16.57	10.30	2.44	7.86	6.27	....
Apr. 1937-											
Sep. 1937	63.8	27.80	9.55	-3.20	6.35	21.45	12.83	4.93	7.90	8.62	....
Oct. 1937-											
Mar. 1938	44.1	35.46	9.74	+3.60	13.34	22.12	10.46	3.12	7.34	11.66	20.28
Apr. 1938-											
Sep. 1938	64.7	39.16	15.74	-2.95	12.79	26.37	16.74	5.45	11.29	9.63	....
Oct. 1938-											
Mar. 1939	45.0	49.04	26.24	+5.10	31.34	17.70	9.91	2.30	7.61	7.79	17.42
Apr. 1939-											
Sep. 1939	64.2	26.96	11.05	-5.67	5.38	21.58	12.05	3.90	8.15	9.53	....
Oct. 1939-											
Mar. 1940	40.8	24.08	4.09	+1.77	5.86	18.22	6.25	2.00	4.25	11.97	21.50
Apr. 1940-											
Sep. 1940	62.8	37.34	12.26	-1.05	11.21	26.13	14.42	4.94	9.48	11.71	....
Oct. 1940-											
Mar. 1941	42.8	24.85	8.75	+0.90	9.65	15.20	7.75	1.61	6.14	7.45	19.16
[a] Apr. 1941-											
Sep. 1941	66.2	25.18	13.48	-0.78	12.70	12.48	12.55	1.92	10.63	-0.07	....
Oct. 1941-											
Mar. 1942	43.7	37.18	23.15	+4.62	27.77	9.41	9.32	1.82	7.50	-0.09	0.00
Apr. 1942-											
Sep. 1942	66.1	34.56	18.38	-3.08	15.30	19.26	16.18	2.12	14.06	3.08	....
Oct. 1942-											
Mar. 1943	43.2	43.84	28.50	+2.95	31.45	12.39	9.50	1.84	7.66	2.89	5.97
Apr. 1943-											
Sep. 1943	65.8	40.63	20.25	-3.23	17.02	23.61	17.68	2.07	15.61	5.93	....

[a] Vegetation cut January to March, 1941.

The results to date indicate that in this locality a forest-stand with an understory of dense shrub annually uses from 17 to 22 inches of water in transpiration. Removal of this vegetation has been shown to increase stream-flow by an amount equal to the estimated transpiration if sprout-growth is prevented. The largest increases to stream-flow occur during the fall replenishment-period. Greatly increased flow is also caused by periods of heavy rain during the growing season. During the late-winter and early-spring period, runoff is but little affected.

It must be remembered that the soil of the Experimental Watershed was developed under forest-cover and has an exceptionally high infiltration-capacity and favorable porosity and structure for soil-moisture storage. The experiment was designed to protect the soil insomuch as there was a minimum of disturbance to the forest-floor during cutting. Therefore the results apply only to a watershed with a forest-soil but without vegetation. Without the protection of vegetation and the annual addition of large amounts of organic material, forest-soil structure will ultimately break down and the soil will become less favorable for infiltration and moisture-storage. The thousands of acres of eroding land and high peak-discharges from cleared watersheds in the southern Appalachians are a testimonial to this.

The present experiment is a pilot-study to aid in the determination of practical methods of manipulating forest-stands to regulate stream-flow. It indicates the maximum effect that may be achieved by reducing forest-cover in a superhumid climate.

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DISCUSSION

R. W. DAVENPORT (U. S. Geological Survey, Washington 25, D. C.)--The results of the experiment described in this paper are based on a study of differences between precipitation (P) and runoff (R). It is interesting to compare the data for the small experimental areas and those for the inclusive basin, Little Tennessee River at Judson, North Carolina (664 square miles), and the neighboring basins, Tuckasegee River at Dillsboro, North Carolina (347 square miles), and Nantahala River at Almond, North Carolina (174 square miles) as shown in Table 1. The figures for average annual precipitation on the river-basins are those furnished in Tennessee Valley Authority reports of annual precipitation in the Tennessee River-Basin and since these are available for calendar years the other data are presented on that basis also. The runoff-data are those of the United States Geological Survey, being published for all years except 1941 and 1942, which are furnished provisionally.

The precipitation on the experimental areas is greater than that on the river-basins, whereas the runoff-rates for the two groups are more nearly of the same magnitude. It follows that the values of (P-R) for the experimental areas tend to be materially greater than those for the river-basins, except in respect to the years 1941 and 1942 on Area No. 17 after the removal of forest-vegetation, when the value was 28.97 inches as contrasted with a weighted average of 30.1 inches on the river-basins.

Any errors in the data for the river-basins would be reflected directly in the above results. It seems unlikely, however, that they would be of a magnitude to affect general inferences materially. A mean annual water-loss of 24 to 29 inches for a mean annual temperature of 55°, as seems to characterize these basins, is consistent with results for other basins in the humid parts of the country as graphically represented in Figure 5, page 53, of United States Geological Survey Water-Supply Paper 846, "Natural water loss in selected drainage basins", by G. R. WILLIAMS and others.

Although the magnitudes of the values of (P-R) on Area No. 17 for 1941 and 1942 and on the river-basins are about the same, it appears that they are constituted quite differently. The former includes more soil-evaporation and very much less transpiration than the latter. Deep seepage, or the seepage which does not return as stream-flow in the drainage-basin considered, but passes out of that basin through the ground, is an unknown factor in each instance. It is, however, more likely to be an appreciable factor for small headwater-basins like the experimental areas. This would depend on the effectiveness of the cutoff-walls at the measuring weirs in intercepting all subsurface-flow from the basin.

Great care was evidently taken to protect the surface of Area No. 17 during the cutting so that conditions influencing infiltration would not be changed. Nevertheless, the consequent difference in exposure of the surface to Sun, wind, and rain, seemingly may have been very marked. There was higher soil-moisture and more soil-evaporation. Considering the variability and complexity of the process of infiltration, it is suggested that these changes may have modified rather materially the system of absorption and storage of water in the ground. It seems conceivable that a

Table 1--Comparison of precipitation (P), runoff (R), and (P-R) in mean depth in inches, for experimental areas and neighboring river-basins, 1937 to 1942

Year	Experimental areas				
	P	Area 17 (32.8 acres)		Area 18 (30.8 acres)	
		R	(P-R)	R	(P-R)
1937	68.98	30.93	38.05	37.40	31.58
1938	71.33	27.03	44.30	32.93	38.40
1939	66.71	34.02	32.59	41.76	24.95
1940	69.27	18.64	50.63	23.00	46.27
1941	51.36	25.73	25.63	17.18	34.18
1942	76.90	44.58	32.32	35.36	41.54
Means					
1937-40	69.07	27.66	41.41	33.77	35.30
1941-42	64.13	35.16	28.97	26.27	37.86
1937-42	67.43	....	....	31.27	36.16

Year	River-basins								
	Little Tennessee at Judson, N. C. exclusive Nantahala at Almond, N.C. (490 square miles)			Tuckasegee at Dillsboro, N.C. (347 square miles)			Nantahala at Almond, N.C. (174 square miles)		
	P	R	(P-R)	P	R	(P-R)	P	R	(P-R)
1937	60.1	32.9	27.2	61.6	34.8	26.8	63.3	41.1	22.2
1938	55.0	26.4	28.6	54.8	28.1	26.7	64.1	40.4	23.7
1939	51.4	28.5	22.9	52.5	29.3	23.2	55.2	36.4	18.8
1940	55.8	22.9	32.9	57.9	28.5	29.4	56.0	29.9	26.1
1941	46.9	18.1	28.8	46.9	19.5	27.4	50.1	24.5	25.6
1942	66.6	31.2	35.4	63.6	30.4	33.2	70.8	41.0	29.8
Means									
1937-40	55.6	27.6	28.0	56.7	30.2	26.5	59.6	36.9	22.7
1941-42	56.8	24.6	32.2	55.3	25.0	30.3	60.4	32.7	27.7
1937-42	55.9	26.6	29.3	56.2	28.4	27.8	59.9	35.5	24.4

train of adjustments was set in motion which would require more than two or three years to reach equilibrium.

Table 2 shows ground-water storage in inches on March 31 and September 30 for Area No. 17 as computed from Column (4) of Table 2, assuming the storage on September 30, 1936, as the reference-datum.

Table 2--Ground-water storage, Area 17

Year	Mar. 31	Sep. 30
1936	....	....
1937	+2.47	-0.73
1938	+2.87	-0.08
1939	+5.02	-0.65
1940	+1.12	+0.07
1941	+0.97	+0.19
1942	+4.81	+1.73
1943	+4.68	+1.45

These data indicate that the average ground-water storage was probably definitely greater in the latter part of the test-period. The higher base-flow probably associated with the higher runoff after the cutting of vegetation, would also indicate that higher ground-water storage prevailed. Such a condition would be favorable to an increase in deep seepage. It may be noted that Column (4), "Change in storage", represents the part of ground-storage which ultimately appeared as ground-water runoff, probably based largely on depletion-characteristics before the cutting. It is suggested that more or less radical changes in the intake- and outgo-systems of infiltration, transpiration, and soil-evaporation, may have induced changes in the ground-storage system so that the previous calibration would not apply.

Quite likely the questions raised concern the close quantitative accuracy of the results of the experiment, more than their broad significance. It is believed, however, that the points might well be kept in mind in practical applications and in comparisons with other data.

The project, exemplified by this experiment, to secure factual data as an aid to understanding the relation of forest-stands to the hydrologic cycle, cannot be commended too highly and the Forest Service and the author are to be congratulated for making the results available to the public.

M. D. HOOVER (closure)--Mr. DAVENPORT has called attention to an extremely important point in the interpretation of watershed-studies. Caution with regard to the possibility of seepage-losses to runoff from small drainage-areas is necessary. This is particularly true where a water-cycle component is estimated as a residual. However, in the study of the two watersheds reported, the method of determining the increases to runoff after cutting (Table 1) largely eliminates any possibility of seepage influencing the results. The increase to runoff is estimated on the basis of the relation between runoff from the two areas before and after treatment. Seepage would not affect the results unless its amount changed during the course of the experiment. There is no indication of such a change. As an additional precaution, runoff from the control-area (No. 18) was compared with another untreated watershed for the periods before and after treatment. The relationship between runoff from these two areas was similar for both periods, demonstrating that no important change in seepage occurred on the control-area.

Another cutting-study on the Coweeta Experimental Forest provides a check on the reasonableness of the results. A 40-acre watershed was cut in a similar manner to Area No. 17 during the winter of 1939-40. No sprouting was done and natural regrowth was allowed. By comparison with its control-area, the increase to runoff from April, 1940, through March, 1941, was 16.4 inches. The increase to runoff was 17.3 inches for the first 12 months after cutting Area No. 17.

At the Coweeta Experimental Forest, stream-flow has been measured for 30 watersheds which range in size from four to 4000 acres. Seventy-five non-recording and 12 recording rain-gages furnish a very good precipitation-record. These observations permit evaluation of water-loss for areas of relatively uniform hydrologic characteristics. Such areas furnish the best information for practical studies of the relation of land-use to the water-cycle. Water-losses estimated for large streams are a weighted average for many diverse areas. Such estimates are valuable for many uses but may not represent any specific hydrologic unit. Even within the Coweeta Experimental Forest, it has been found that water losses differ by areas with aspect, soil-profile characteristics, vegetation, and seasonal rainfall-distribution. There is a definite pattern of water-loss on this Forest and the results for Areas Nos. 17 and 18 fit into this general pattern.

FORECASTING SPRING RUNOFF FROM SNOW-SURVEYS FOR PEMIGEWASSET RIVER AT PLYMOUTH, NEW HAMPSHIRE

Charles C. McDonald

The reliability of forecasts of spring runoff by means of snow-surveys has been established by many years of accurate forecasting, particularly for basins where the greater part of the spring runoff is derived from snow-melt. In much of the western portion of the United States, the amount of precipitation received during the melting-period is a small proportion of the accumulated snowfall. Where these conditions exist, accurate forecasts are possible provided sufficient data are available to define the relation between water-content of the snow-mantle and runoff. However, in the northeastern part of the United States the amount of rainfall received during the melting-period may be equal to or greater than the water-content of the snow-mantle at the beginning of the melting-period. The segregation of runoff received from snow and that received from rainfall during the melting-period is impossible, and the volume of spring runoff depends to a great extent upon the amount of the spring precipitation.

The accuracy of forecasts of the spring runoff under these conditions is limited by the possible variation in the spring rainfall. Since rainfall cannot be accurately predicted, forecasts of the runoff must necessarily make allowance for possible deviations from normal rainfall. Forecasts of this type are valuable, however, in defining the probable limits of the spring runoff. The practical value of such forecasts has been discussed by PAUL L. BEAN [see 1 of "References" at end of paper] for the Androscoggin River in Maine.

This paper describes a method of forecasting which makes possible a direct valuation of the effect of rainfall during the melting-period. The principles involved are not original, and the records are not of sufficient length to define accurately the relation of runoff to water-supply nor to prove conclusively the reliability of this relationship. However, it is believed that the application of this method to a New England watershed may prove of interest and value to hydrologists of

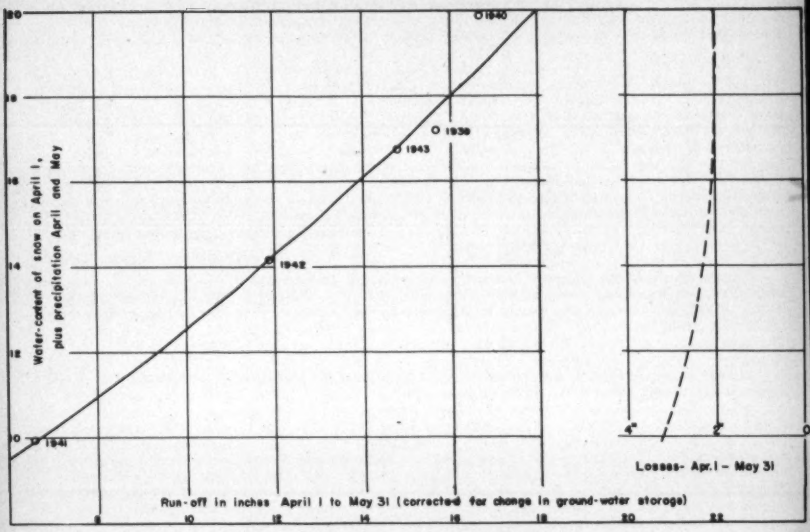

Fig. 1--Relation of water-supply and runoff

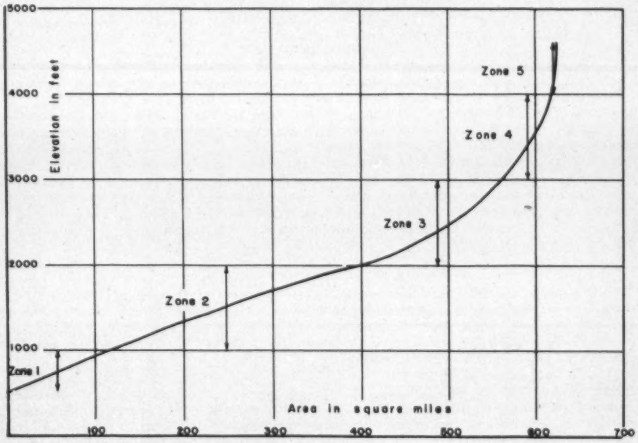

Fig. 2--Relation of area and elevation

New England and to the Section of Hydrology of the American Geophysical Union.

A quantitative estimate was made of the water-content of the snow-mantle, in inches over the watershed, for April 1 of each year since snow-surveys were started in 1939. To this value was added the precipitation received during April and May. The sum represents the total available water-supply during these two months. Of this quantity, a certain portion is lost by evaporation and transpiration, some may be held in ground-water storage at the end of May, and the remainder appears as stream-flow at the outlet of the basin. The total water-supply is plotted against runoff in Figure 1. In order to eliminate the effects of varying ground-water storage on the water-supply-runoff relation, the runoff was adjusted for the estimated change in ground-water storage between April 1 and May 31. Thus the losses are limited to those due to evaporation and transpiration.

Description of the Drainage-Basin--The basin of the Pemigewasset River above Plymouth, New Hampshire, consists of 622 square miles of mountainous and wooded country and is the main tributary of the Merrimack River. The average land-slope is greater than for any drainage-area of comparable size in Massachusetts, Vermont, and New Hampshire except for the White River-Basin and possibly the Winooski River-Basin in Vermont. The normal yield of the basin is unusually high. The elevation varies from 500 feet at the mouth to about 4,500 feet at the highest point, with a median elevation (50 per cent of the area above, and 50 per cent below) of 1,760 feet. The area-elevation curve for the basin is shown in Figure 2.

Snow-surveys--Snow-surveys in this basin were begun by the New Hampshire Public Service Company during the winter of 1938-39 and have been continued to date through the cooperation of the United States Engineer Department. The method of making the surveys and the location of the snow courses were discussed by J. V. SALO [2]. Snow-surveys are made from two to four times each year, the last survey being made about April 1. The maximum water-content normally occurs sometime during the latter part of March or early in April.

Determination of the water-content of the snow-mantle--An attempt has been made to determine quantitatively the water-content of the snow-mantle on April 1 of each year. As pointed out in Mr. SALO'S paper, there is a definite relation between the water-content of the snow and the elevation. The variation of the water-content-elevation curve as the season progresses is shown in Figure 3. In this Figure, average water-content-elevation curves are shown for February 1, March 1, and April 1. The curve for April reflects the loss in accumulated snow for the lower elevations and the increase in accumulation for the higher elevations. In order to arrive at the most accurate estimate possible of the volume of water in the snow-mantle, the basin was divided into five zones according to elevation. The areas between 500 and 1,000 feet and between successive 1,000-foot contours above were determined by planimeter.

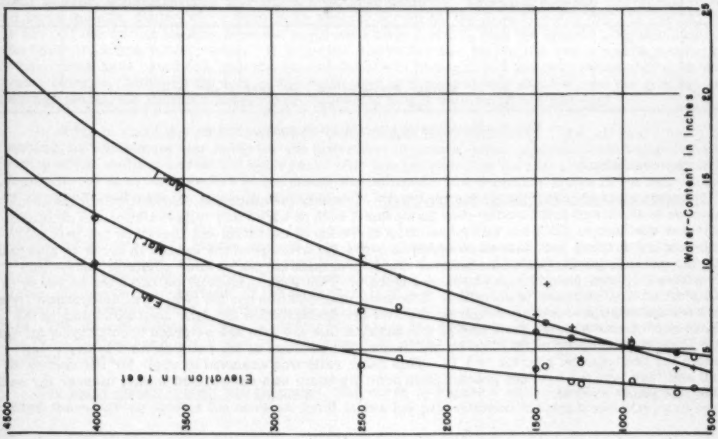

Fig. 3--Relation of water-content and elevation (5-year averages)

The water-content at the median elevation (50 per cent of the area above and 50 per cent below) for each zone was assumed to represent the mean for the zone, and was determined from the water-content-elevation curve for April 1 of each year. The depth of water over the basin was determined by weighting the mean for each zone according to the area of the zone.

Values of water-content computed in this manner are slightly higher than those computed by the "mean-elevation-of-the-basin" method used by Mr. SALO. However, it is believed that the data are sufficiently complete to justify the use of this method, and that the values are probably

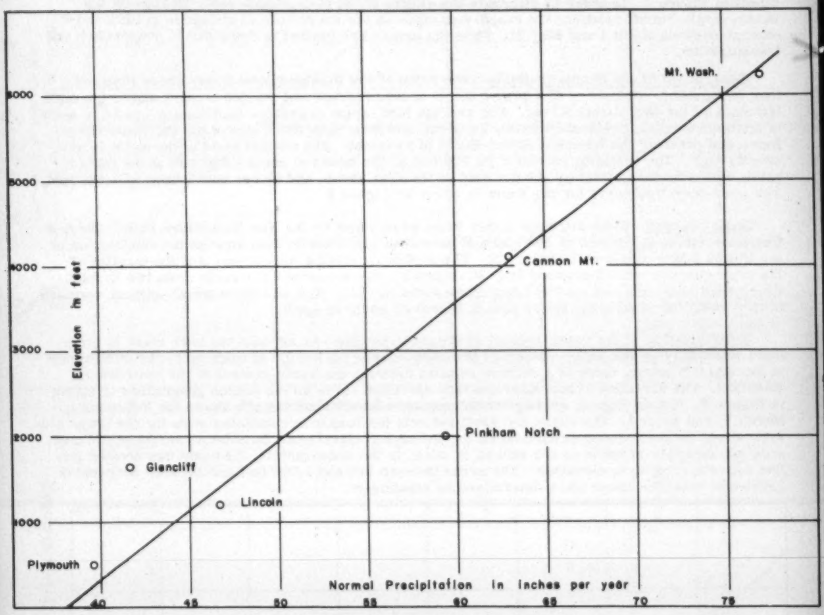

Fig. 4--Relation of precipitation and elevation

more representative.

Determination of precipitation for the Basin--The only precipitation-stations within the basin are those at Plymouth and Lincoln, New Hampshire, both of which are valley-stations at comparatively low elevations. Both are below the mean elevation of the basin and therefore the precipitation recorded at these two stations probably is below the average of the basin. In order to approximate the average for the basin, the normal yearly precipitation for several points in the vicinity was plotted against elevation as shown in Figure 4. This Figure clearly indicates the increase in precipitation with increase in elevation. The mean precipitation for the basin was determined from this average relation-curve by weighting the average precipitation for each zone according to the area of each zone. It was determined in this manner that the average weighted precipitation for the basin for any year could be obtained by multiplying the average of the records for Plymouth and Lincoln for that year by a factor of 1.12. This same ratio was assumed to apply for the months of April and May, and the average precipitation over the basin was determined in this manner for each of the five years studied.

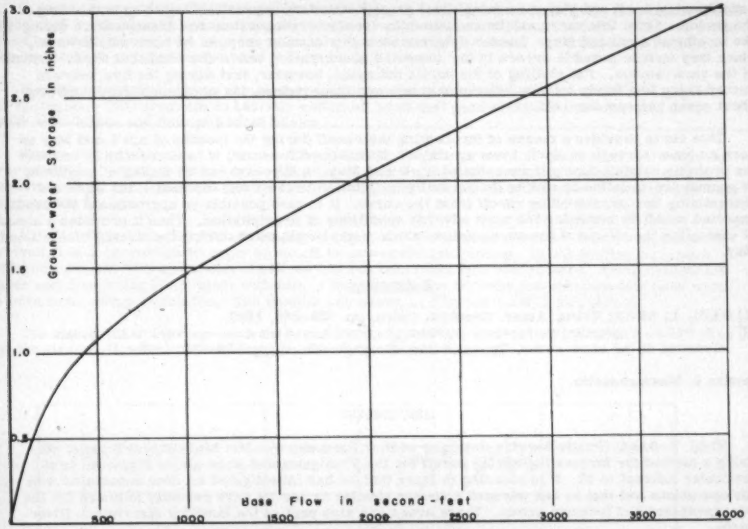

Fig. 5--Relation of ground-water storage and base-flow

Estimate of ground-water storage--The influence of ground-water storage on the spring run-off, and consequently on the relationship between the snow-cover and subsequent runoff, is demonstrated by this study. The relative height of the water-table for April 1 varies considerably from year to year, depending upon antecedent weather-conditions. After a prolonged cold period of two or three months, during which very little melting occurred, the ground-water table is comparatively low. If the spring melting does not begin until after April 1, then the amount of ground-water in the basin is comparatively small. If, however, the winter has been mild, and frequent melting or winter rains have occurred, then the ground-table will be high, with corresponding high ground-water storage. Although the soil in this watershed is comparatively shallow, and the ground-water storage small, the possible influence on the spring runoff may reach ten per cent.

In order to make the relation between water-supply and runoff (Fig. 1) for all years more comparable, an adjustment was made for the difference in ground-water storage at the beginning and ending of the melting-period for each year. For this purpose, the normal ground-water (base-flow) depletion-curve of stream-flow at Plymouth was utilized. The depletion-curve is the hydrograph of stream-flow during dry periods when water is being drawn entirely from ground-water sources. The area under the curve represents the net amount of ground-water storage available for stream-flow and is a measure of the total ground-water storage in the basin. In Figure 5, the volume of ground-water storage is plotted against base-flow. This curve is therefore a capacity-curve for ground-water storage, using base-flow at Plymouth as an index. By determining the rate of base-flow from ground-water sources at any particular time, a measure of the net available ground-water storage is thus obtained. If the base-flow is higher at the end of the runoff-period than it was at the beginning, then a portion of the available water-supply has gone into ground-water storage. The amount of this storage is obtained by taking the difference in the quantities represented by the base-flow on April 1 and May 31. The runoff for each year was adjusted by this amount before plotting Figure 1.

The water-supply-runoff relationship-- The curve in Figure 1 expresses the relationship between the water-content of the snow on April 1 plus the precipitation for April and May, and the

runoff during April and May, assuming equal ground-water storage at the beginning and ending of the period. From this curve can be computed the losses by evaporation and transpiration during the months of April and May. Losses determined in this manner may not be accurate, however, since they include possible errors in the computed precipitation and in the computed water-content of the snow-mantle. The plotting of the points indicates, however, that during the five years of record there is a fairly definite relationship between these values, the greatest difference being about seven per cent for 1940.

This curve provides a means of forecasting the runoff during the months of April and May as soon as snow-surveys on April 1 are available. In making a forecast, it is necessary to consider the probable rainfall during the months of April and May. A forecast can be made for conditions of normal precipitation by adding the normal precipitation to the water-content of the snow and determining the corresponding runoff from the curve. It is also possible to approximate the lowest expected runoff by assuming the most adverse conditions of precipitation. Thus it provides a means of evaluating the effects of the precipitation which might be expected during the months of April and May.

References

[1] PAUL L. BEAN, Trans. Amer. Geophys. Union, pp. 835-846, 1940.
[2] J. V. SALC, A quantitative forecast-system of runoff based on snow-surveys at the mean elevation of the snow-cover, Trans. Amer. Geophys. Union, pp. 858-870, 1940.

Boston 9, Massachusetts.

DISCUSSION

JOHN V. SALO (Public Service Company of New Hampshire)--Mr. McDONALD'S paper outlining a method for forecasting spring runoff for the Pemigewasset Area above Plymouth is of particular interest to us. It is pleasing to learn that he has investigated an area associated with our operations and that he has pursued a course similar to one we have recently followed for the Winnepesaukee and Jackman areas. These areas are also part of the familiar Merrimack River-Basin.

Though these areas necessarily differ as to the time of start of spring runoff, we agree that the approach to the forecasting problem must be based upon the water-content of the snow-cover just before runoff begins, plus the additional precipitation occurring during the runoff-period.

Good forecasts require that a snow-survey be made at about the time that water-content is maximum, and just before runoff starts. We have not always abided by this requirement for one reason or another. The Plymouth Area has fared better and it is recommended that the record established for snow-surveys made regularly each year covering the last days of March be continued.

We find, in general, that runoff begins by March 10 in the Winnepesaukee and Jackman areas. It is desirable to plan for a survey to occur during the last week of February or the first week in March. The runoff for the area above Plymouth begins approximately two weeks later. The continued build-up of snow-cover above Plymouth is a result of a combination of higher elevations, lower temperatures, less likelihood (though never impossible) of heavy rains in March, and a deeper snow-cover capable of absorbing rain and slush in amounts as large as one-inch storms.

The method of weighting snow-cover data by zones to determine average water-content for an area is an improvement over the sub-division method referred to by Mr. McDONALD, which we formerly used. It is much less laborious, faster, and produces an average which is representative of the entire area considered. To obtain satisfactory results with this method it is desirable that snow-courses be located at a wide range of elevations, particularly the higher elevations. The Pemigewasset Area is now well covered with courses through the efforts of the United States Army Engineer Office. Enough data are thus available to make a satisfactory working basis.

The estimate of average precipitation which occurs during the runoff-interval is more liable for error. The data for the basis of this estimate are not as plentiful as for snow-cover. The snow-courses in the Pemigewasset Area and other areas now outnumber the precipitation gaging-stations. Naturally most of the precipitation-gages are located at the accessible lower elevations. We all agree that the amount of precipitation which is recorded by these gages is smaller than the amounts falling on the higher elevations (including the mean elevation).

It would be very desirable to have unattended gages established at the higher elevations. These gages need be checked but once every two weeks or even at the end of each month. The data which would be available would be of much value in general, and in particular to forecasts of runoff requiring the best possible estimate of precipitation.

We understand that efforts are in progress to promote the installation of unattended gages in the northeast. This program is heartily endorsed by us and good locations are available in the upper Merrimack and Pemigewasset basins.

These will provide a basis for checking and adjusting the present methods used for weighting precipitation. As precipitation in the Merrimack and Pemigewasset basins during the runoff-period totals 50 per cent to 75 per cent of the total water-supply, the importance of additional data is apparent.

Mr. McDONALD'S analysis of the significance of the change in ground-water storage and the derivation of a correction to apply to runoff is extremely interesting. In our preliminary work with Jackman and Winnepesaukee areas we had not taken this fact into account. After reading his paper and discussing the subject with him, I looked over the records and obtained data upon which to base some rough estimates. The results are shown in Figures 1 and 2 as curve B.

The recognition of this ground-water relation suggests the interesting possibility of forecasting the stream-flow for the few weeks following the runoff-interval.

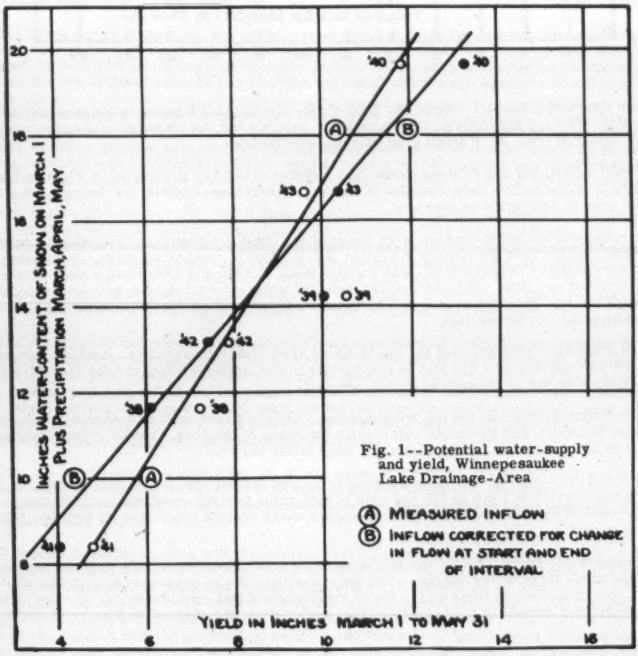

Fig. 1--Potential water-supply and yield, Winnepesaukee Lake Drainage-Area

(A) MEASURED INFLOW
(B) INFLOW CORRECTED FOR CHANGE IN FLOW AT START AND END OF INTERVAL

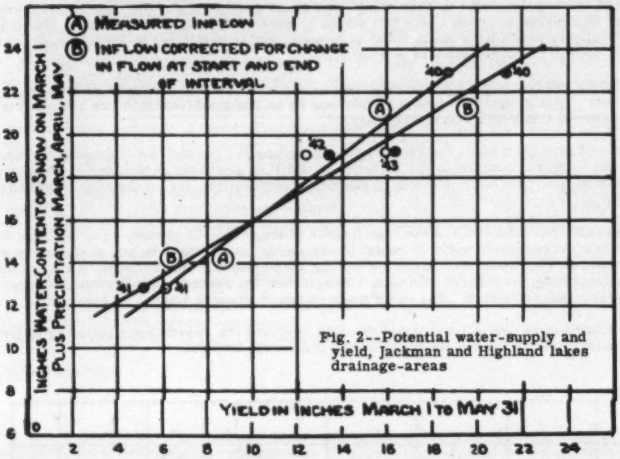

Fig. 2--Potential water-supply and yield, Jackman and Highland lakes drainage-areas

Another interesting subject outside the field of Mr. McDONALD'S paper is the forecast of the time of runoff. Perhaps the analysis of temperature-records and the invention of a degree-day based upon deviation from 32°F might give valuable information.

The runoff results for the Winnepesaukee and Jackman areas are illustrated in Figures 1 and 2. As the range of elevation for snow-courses is limited, a percentage-method for weighting the water-content was used to determine an average.

Four representative snow-courses were selected for the Winnepesaukee Area of 363 square miles. These courses have an average elevation of 1,115 feet in comparison to the mean elevation of 730 feet for the area. Inspection of eight surveys made in 1939 and 1940 when a quantitative subdivision method was used indicated that the weighted water-content for the area averaged about 84 per cent of the four selected courses. The weighted water-content for the following years was determined by using this percentage.

Four courses were also selected for the Jackman Area of 64 square miles. As the average elevation of these courses of 1,512 feet is comparable to the mean elevation for the area of 1,440 feet the weighting-factor is considered as 100 per cent.

The precipitation-estimate for the Winnepesaukee Area is based on the average of three gages--New Durham, Lakeport, and Plymouth--located on the edges of the area. The average elevation of these gages is 537 feet and the weighting-factor used is 105 per cent.

The precipitation-gage for the Jackman Area is located outside the area at an elevation of 600 feet. The weighting-factor used is 125 per cent to determine average precipitation. This gage-record was checked against increases in snow-course water content which give an average difference of 25 per cent.

The ground-water correction for the Winnepesaukee areas has been a little difficult to determine because of the large water-surface of 68 square miles. It was necessary to plot the lake-inflow on a second-foot-week basis as the finest measurement that could be made. In view of this and the considerable amount of loss possible from evaporation, the correction may be in error.

ACCURACY OF STREAM-FLOW RECORDS

G. K. Wood

The collection of stream-flow data by the United States Geological Survey began in 1888 and has continued without interruption since that time. It has increased to the extent that more than 5,000 gaging-stations are now being operated throughout the United States and the Territory of Hawaii in cooperation with States, Federal bureaus, municipalities, and other agencies. Results of this work are published annually in United States Geological Survey Water-Supply Papers.

With the expansion of the stream-gaging program, there has been a continual improvement in the accuracy of the stream-flow records. It is the purpose of this paper, first, to discuss briefly the various factors influencing or affecting the accuracy of these records as a whole, without special reference to the accuracy of records of floods or droughts, complete coverage of which would require a separate paper and, second, to present examples illustrating the accuracy of discharge-data obtained by methods of the Survey as determined by comparison with stream-flow records computed by other methods of recognized accuracy.

Factors affecting the accuracy of stream-flow records--Included in the description of each gaging-station in every Water-Supply Paper is a statement concerning the accuracy of the records for that station. A rating of "excellent" is given to those daily records which are believed to be accurate within five per cent, "good", within ten per cent, "fair", within 15 per cent, and "poor", probably not within 15 per cent. The four factors which determine this accuracy are as follows: (1) Discharge-measurements; (2) stage-discharge relation; (3) observation of stage; and (4) interpretation of data.

Discharge-measurements-- Discharge-measurements, with the possible exception of measurements of extremely high or extremely low discharge, are made by the velocity-area method using the small PRICE current-meter. All current-meters are rated individually for the Survey by the National Bureau of Standards. Ratings for the individual meters are accurate to within one per cent.

It is sometimes necessary to determine flood-flows by special methods. Slope-area, contracted-opening, computation of flow over dam, and critical-depth are some of the methods used. Also, in order to obtain greater accuracy, extremely low discharge is often determined by volumetric method, portable weir, PARSHALL flume, special pygmy current-meter, and other methods. However, the usual practice of the Survey is to obtain measurements by PRICE current-meter.

The degree of accuracy with which discharge-measurements can be made at a gaging-station is an important factor in the determination of the accuracy of the daily discharge-data. The same accuracy cannot be obtained at all stations, and the accuracy of the individual measurements at the same station may vary from time to time. The measuring equipment, roughness of the stream-bed, smoothness and velocity of the flow, depth, angle that the current makes with the measuring-section, drift, weather-conditions, whether stage is constant or changing--these are some of the more important factors affecting the accuracy of the individual measurement.

The accuracy of discharge-measurements, and consequently of discharge-records, has increased considerably in recent years as a result of improvements in measuring-equipment. The use of heavy weights, reels, and cranes has made possible greater accuracy in flood-measurements since depths can be more accurately determined and the meter more readily held in its proper position. Power-driven equipment is used for handling the heavier weights that are used at some of the stations on the Mississippi River and other large streams. More extensive use of cableways for measuring sections has improved measuring-conditions.

For low discharges, considerable use is now being made of the pygmy current-meter which has been developed by the United States Geological Survey in the past few years. It is a very small vertical-shaft meter of the PRICE type which enables greater accuracy to be obtained in the measurement of very shallow streams.

For most accurate results with the current-meter, it is desirable that the stream at the measuring-section have a smooth bed, that there be little turbulence (as serious turbulence may cause over registration in a vertical-shaft meter), that piers and other obstructions do not seriously affect the flow, that the stage be fairly steady during the measurement, that drift, aquatic vegetation, or ice do not interfere with the operation of the bucket-wheel of the meter, that there be little or no angle of the current with the measuring-section, that there be no strong wind affecting the velocity of the stream near the surface, and that the proper measuring-equipment be available. Although it

is not always possible for all of these requirements to be met, these factors are considered in the selection of the measuring-section.

The mean gage-height for a measurement is equally as important as the measured discharge in the definition of the stage-discharge relation. Consequently, it is desirable that the measurement be made under conditions which permit the exact determination of gage-height. It is important also that the measuring-section be near the gage.

Given the best of the above conditions, the measured discharge is likely to be within two per cent of the true discharge and the measurement is considered excellent.

Stage-discharge relation--A control is the physical feature of a stream, downstream from the gage, that determines the relation between stage and discharge at the gage. It may be a single section of the stream-channel, a long stretch of channel, or an artificial structure. Whatever type it is, there is probably no other single factor that has more effect on the accuracy of the station-records.

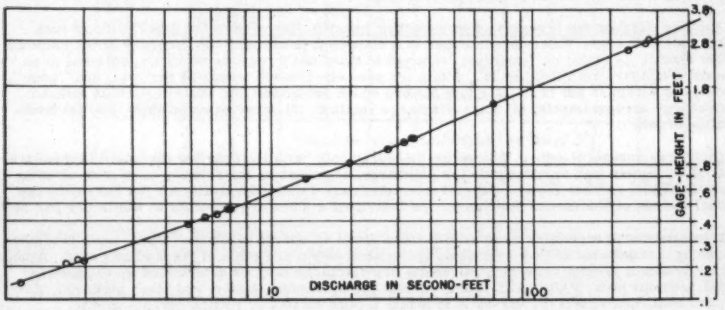

Fig. 1--Rating-curve for Oyster River near Durham, New Hampshire

A control may be stable, such as a ledge-rock falls, or it may be one whose physical features change, causing frequent changes or shifts in the stage-discharge relation. A stable control ordinarily produces greater accuracy in the discharge-records. If the stage-discharge relation is stable, ample opportunity is provided for obtaining discharge-measurements at various stages and a rating-curve can be drawn which will define the stage-discharge relation for a comparatively long period of time. Figure 1 shows a rating-curve for a gaging-station which has a permanent concrete control, the measurements shown covering a period of several years.

A control may be stable, but a lack of sensitivity in the stage-discharge relation may prevent the obtaining of highly accurate discharge-data. A sensitive control is one for which a relatively large change in stage is produced by a relatively small change in discharge. Thus, for this type of control, the accuracy to which the stage can be determined will be well within required limits to provide accurate discharge-data. Therefore, if a stable control is also sensitive, the task of obtaining accurate records is considerably reduced.

In recent years, more and more use is being made of artificial controls. An artificial control usually consists of a low dam, weir, or flume, located immediately downstream from the gage. It tends to stabilize the relation between stage and discharge and provides proper sensitivity, particularly at low stages. In addition, it often eliminates or decreases the backwater-effect from ice and aquatic vegetation. Usually, a control of this type is not effective at all stages as ordinarily it cannot be built high enough to prevent submergence at high flows. Artificial controls tend to improve accuracy, but it is not correct to assume that records for stations having such structures are always more accurate than records for stations having only controls provided by nature.

Unfortunately, some gaging-stations have poor measuring-sections. Consequently, even though the control be stable and sensitive, measurements may scatter considerably on the rating-curve,

making it difficult to define the rating-curve as accurately as might otherwise be possible. It should be noted, however, that, with a stable control, a rating-curve drawn to average a group of measurements is more accurate than the individual measurements. Measurements may scatter considerably but if they are averaged by the rating-curve much of the error is eliminated. The accuracy of the rating-curve is an important factor in determining the final accuracy rating of the discharge-record. Spacing of measurements on the rating, the extent to which the curve is actually defined by measurements, whether it was necessary to extend the rating either above or below the measurements, are some of the details to which the engineer gives consideration in assigning the final accuracy-rating.

It is often impossible for various reasons to locate a gage so that a stable relation between stage and discharge can be obtained. In these instances, discharge-measurements must be made much more frequently. The accuracy of the individual measurements and the frequency with which they are made at this type of gaging-station have more effect on the accuracy of the computed records than at a gaging-station that has a permanent relation between stage and discharge. At some gaging-stations, on the Mississippi and Colorado rivers, for example, measurements are sometimes made daily because of continual shifting of the control. By obtaining measurements as frequently as this, it is possible to compute accurate records. However, limitations in funds and personnel usually prevent the obtaining of such frequent measurements, and it is, consequently, often necessary to decrease the accuracy-ratings for stations subject to "shifting control", rating them "fair" or "poor". The records that are qualified as "good" or "excellent" are more often obtained for those streams which have stable controls.

Even at a gaging-station which has a stable control, there may be periods during the year when the control is affected by a temporary backwater-condition. This is particularly true of gaging-stations in those parts of the United States where sub-freezing temperatures prevail for long periods. The stage-discharge relation is often affected by backwater from ice, either continuously or intermittently throughout the winter, and in the absence of daily measurements it is usually necessary to lower the accuracy-rating for these periods. They are computed by special methods, usually on a basis of weather-records, observer's and engineer's notes, power-plant records, and comparison with records for stations on nearby streams, in addition to the usual gage-height record and discharge-measurements.

At many gaging-station sites throughout the United States the stage-discharge relation is affected by aquatic vegetation and may be unstable even if the vegetation at times disappears from the stream. For gaging-stations that are subject to this condition, only frequent discharge-measurements will enable the computation of accurate discharge-data.

Observation of stage--The stage-record from which the daily discharge is determined is obtained either by a water-stage recorder or is based on an observer's readings. The water-stage recorder provides a continuous record, while the gage-height record obtained by an observer usually consists of two readings a day. The trend for many years has been toward supplanting the observer's readings by the recorded graph, thus producing a more accurate stage-record. On a stream that has rapid diurnal fluctuation due to power-plant regulation or that is otherwise subject to sharp and large changes in stage, it is impossible to obtain accurate discharge-data without a water-stage recorder. The modern recorder may, under the best conditions, provide a gage-height graph that is correct to 0.01 foot or less. Time-marking and reversal-indicating devices further increase its accuracy. At a gaging-station that has a non-sensitive control, the accuracy of the records can often be improved by a recording-gage that has a gage-height ratio which permits the stage to be determined accurately within a few thousandths of a foot.

It is not correct to deduce from the foregoing that accurate records of stage are obtained only by recording-gages. If a stream is not "flashy" but is the sluggish type that rises and falls very slowly, the mean of two gage-readings a day may represent closely the actual mean stage. The accuracy of the gage-height record has a most important part in determining the accuracy of the final computed discharge.

It should be mentioned that, regardless of whether the record of stage is obtained by automatic recorder or by observer, keeping the gage at the correct datum is a requisite for an accurate stage-record. This is done by providing a permanent reference-gage which is checked by levels once a year or oftener and by frequent inspections of the recorder to see that it is in agreement with the reference-gage.

Interpretation of data--The basic field-data consist mainly of discharge-measurements and gage-height record. With sufficient discharge-measurements and a complete and accurate record of stage, the engineer has the basis for computing the discharge-records. This information alone, however, does not insure the computation of accurate results. Final accuracy depends on the manner in which the data are interpreted. The experience, judgment, training, and skill of the engineer making the computations influence the accuracy of the final results. The more complete the field-data, the less difficult it is to interpret them properly and the more likely it is that the record will be properly rated "good" or "excellent". Insufficient discharge-measurements and incomplete gage-height recordsare responsible for more "fair" and "poor" records than all other causes.

Thus if "good" or "excellent" records are to be obtained, it is requisite that sufficient accurate discharge-measurements be made to insure an exact definition of the stage-discharge relation at all times, that there be a complete and accurate record of stage, and that the basic data be correctly interpreted.

Accuracy of Survey discharge-data as determined by comparison with stream-flow records computed by other methods of recognized accuracy--Opportunities for comparison between discharge data collected by the usual methods of the Survey and data computed by other methods of recognized accuracy are infrequent. There have, however, been some occasions when such comparisons could be made. The comparisons have been of two types: (1) A comparison between an individual discharge-measurement and a determination of discharge by an independent method; and (2) a comparison between daily, monthly, or yearly discharge-records and similar discharge-records computed by other methods of recognized accuracy. Comparisons of the second type are likely more valuable, in that all factors that affect the accuracy of stream-flow records are reflected in the comparison. There follow a few examples of each type of comparison with individual measurements of flow compared first.

In 1927, H. B. KINNISON, District Engineer, United States Geological Survey, Boston, Massachusetts, made three measurements of discharge of the stream flowing through the Hydraulic Laboratory of the Worcester Polytechnic Institute, located at Chaffinville, Massachusetts. The flow as measured by current-meter about 700 feet downstream from the laboratory was compared with the determination of flow over the weir in the laboratory. The weir had been accurately rated volumetrically by weight, and also by Professor C. M. ALLEN'S salt-velocity method. The discharge as measured by current-meter was 1.75 sec-ft, 24.8 sec-ft, and 30.8 sec-ft. These results varied from the discharge as determined by the weir by +0.6 per cent, -0.9 per cent, and -2.0 per cent, respectively.

At the time of the acceptance tests for the units installed at the Bellows Falls Hydro-Electric Corporation Plant on the Connecticut River at Bellows Falls, Vermont, in 1929, two discharge-measurements were made by the United States Geological Survey and compared with the discharge as determined by the salt-velocity method. The salt-velocity test and the discharge-measurements were made in the canal upstream from the power-plant. The canal had a depth of about 28 feet and the maximum velocity was 6.56 feet per second. Due to a grill-work of pipes located in the canal about 35 feet upstream from the measuring-section for the purpose of distributing the salt solution in the stream, there was some turbulence at the current-meter section which was at the downstream side of a bridge. However the current-meter measurements, made by the 0.2- and 0.8-depth method, differed from the salt-velocity determinations by only +1.2 per cent and +0.3 per cent, respectively.

Four discharge-measurements were made in 1925 by the Madison (Wisconsin) District of the United States Geological Survey for the purpose of checking the wheel-ratings of the Ford Motor Company's Power-Plant at St. Paul, Minnesota. The wheels had been rated by the salt-velocity method. A gate-opening discharge-curve based on the current-meter measurements, crossed the curve determined by the salt-velocity method and differed from it by a maximum of only two per cent [see 1 of "References" at end of paper].

In 1930, the Madison (Wisconsin) District made two discharge-measurements of the Fox River to compare with the computed discharge at the Rapids Croche Dam. The results agreed extraordinarily well, the measured discharges being 1,640 sec-ft and 2,490 sec-ft, and the computed discharges 1,650 sec-ft and 2,480 sec-ft [1].

The United States Geological Survey since 1939 has operated a gaging-station on the Mongaup River near Mongaup, New York. The discharge is determined from two gage-height records, one from a gage located on the tailrace of the Rio Power Plant of the Rockland Light and Power Company, and the other from the gage on the main river-channel upstream from the power-plant but

below the point of diversion. The control for the tailrace-gage is a sharp-crested weir which was installed by the power-company for the purpose of determining the discharge through the plant. In 1939 the weir was rated by the ALLEN salt-velocity method. Five discharge-measurements were made during the three-day period that the salt-velocity tests were made and several measurements had been made previously. Enough salt-velocity tests at different discharges were made to define a curve for the weir based on this method. The average numerical difference from the mean curve for the salt-velocity runs was 2.3 per cent, and the algebraic average +1.8 per cent. The average numerical difference of 14 current-meter measurements from the salt-velocity curve was 3.4 per cent, and the average algebraic difference -0.8 per cent. Two of the discharge-measurements were made at the same time as the salt-velocity runs. One measurement of 609 second-feet agreed within one second-foot of the salt-velocity determination, the other, with a discharge of 825 second-feet, checked within 4 per cent the salt-velocity discharge. It should be stated that measuring-conditions in the tailrace where the current-meter measurements were made were not ideal, the section being somewhat rough, and there was also some turbulence from water discharged through the wheels. Later a group of volumetric measurements were made by the Survey at low discharges in a range in which the head over the weir varied from 0.05 foot to about 0.45 foot. These measurements checked the salt-velocity curve within two per cent [2].

The Tacoma (Washington) District of the United States Geological Survey made a comparison of discharge-data covering a period of several months with discharge-records of the Spokane River near Spokane, Washington. The Washington Water Power Company operated two power-plants about 15 miles apart on the river, both plants having been rated by the Gibson method. The Survey operated gaging-stations a short distance below each plant. During the period compared, the discharge computed by the Survey differed from the discharge determined by the Gibson method by only three per cent, and at least one per cent of this difference was considered due to actual increase in flow between the power-plants and the gaging-stations [3].

The Rolla (Missouri) District operates a gaging-station on the Osage River near Bagnell, Missouri, two miles downstream from the hydroelectric plant of the Union Electric Light and Power Company. Flow through the plant is computed from ratings based on the GIBSON method. The monthly mean discharges during 1933 as determined by the gaging-station were compared with the computed discharge for the power-plant. It was found that they agreed within an average of two per cent and never differed by more than 4.2 per cent [4].

A comparison covering a long period of record has been made by the Albany (New York) District of the Survey. A gaging-station is operated on the Sacandaga River at Conklingville, New York, immediately below a power-plant. Records for this station for the period August, 1932, to September, 1942, have been compared with records computed on a basis of ratings determined by the GIBSON method at the E. J. West Power-Plant at the Conklingville Dam. The two records usually agreed well within five per cent. The yearly mean values were in closer agreement, the range being from -3.7 per cent to -0.4 per cent. The power-plant records for the entire period had a mean deviation of -1.2 per cent [3].

The foregoing comparisons indicate that accurate discharge-measurements are made by methods of the Survey and that these methods enable the computation of accurate discharge-records.

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EVALUATION OF RUNOFF-DISTRIBUTION VALUES FROM BASIC DATA AND STUDY OF RELATED DRAINAGE-AREA CHARACTERISTICS

Karl Jetter

(1) The use of the distribution-graph, or its equivalent, derived from basic rainfall-data and the river-discharge hydrograph, is becoming more widespread in evaluating river-flow characteristics. The major interest in evaluating the distribution-values in this paper was in connection with studies of maximum possible floods on small drainage-areas.

(2) Flood-data are being obtained on an ever-increasing number of streams not only over a range of varying stream-types, but over a considerable range of flood-magnitudes and flood-occurrence. The large number of gaging-stations increases the probability of obtaining good flood-hydrographs in a given area. The greatly increased number of rainfall-stations, particularly of the recording-type, has filled to a reasonable degree one of the main deficiencies in the basic data thus giving more confidence in, and greater incentive to, detailed evaluation as required for obtaining flood-hydrograph distribution-values. Any addition to this type of information, either direct data or on how it may be obtained readily, is of value in utilizing the increased data and in their wider application.

(3) The following describes experience in obtaining distribution-values for small drainage-areas in hilly or mountainous terrain where the streams have little channel-storage. It also includes recognition of suitable types of data and some understanding of the deficiencies inherent in the distribution-graph determination, and a method of indexing, roughly, the physical characteristics of the several drainage-areas as a guide to applying available distribution-values to basins lacking such data. For the type of data available in these studies, a relatively simple tabular procedure was used whereby distribution-values are computed and a satisfactory check had on the reconstituted and original hydrographs. The examples shown are actual occurrences in the upper Merrimack River Basin resulting from the storm of June 14, 15, 1942.

(4) The intense summer storm of June, 1942, covered an area over west central New Hampshire in the upper Merrimack or Pemigewasset River Basin. It produced floods of considerable magnitude on the main stem and tributaries. The streams in the Pemigewasset Basin used in this study have similar runoff characteristics and had adequate rainfall-data and stream-flow data. Well-defined flood-hydrographs were recorded for streams with drainage-areas of 59 to 622 square miles. The rainfall producing significant runoff was confined to about six hours of the storm. In one case runoff up to 3-1/2 inches occurred in one three-hour period. Thus the pluviograph could be divided into but two three-hour periods for the smaller drainage-areas and a single six-hour period covered the runoff-period for the 622-square-mile area. The rainfall-data used were those collected by the United States Weather Bureau and its observers; the stream-flow data were those obtained by the United States Geological Survey at recording-gage stations. Some of both types of data were obtained in cooperation with the United States Army Engineer Office.

(5) The following are the stream-basins and their drainage-areas, for which distribution-values were obtained in this study: East Branch Pemigewasset River near Lincoln, New Hampshire, 104 square miles; Pemigewasset River at Woodstock, New Hampshire, 193 square miles; Pemigewasset River at Plymouth, New Hampshire, 622 square miles; Baker River at Wentworth, New Hampshire, 59 square miles; Baker River at West Rumney (near Rumney), New Hampshire, 143 square miles. Locations of the gaging-stations and precipitation-stations are shown in Figure 1.

(6) The stage-hydrographs at the foregoing river-stations were converted to discharge-hydrographs. The rainfall-data at all stations used were plotted up as mass-curves using the several recording rain-gage stations as guides in adjusting the shapes of graphs at the non-recording rain-gage stations. Hourly precipitation-values were taken from these mass-curves and the average rainfall over the area for each hour was obtained through weighting the individual station-values by use of the THEISSEN method. Figure 2 shows mass-curves of precipitation for the three stations used in the Baker River-Area above Wentworth and the mass-curve representing the weighted average for the basin. The periods used were three hours long for the smaller areas and six hours long for the 622-square-mile area. Using the hourly rainfall-values permitted starting at any hour the period determined from the infiltration-studies as the beginning of effective runoff.

(7) The limitations to the determination of the net or flood runoff-hydrograph and the net or flood runoff-pluviograph are recognized. Reliable data on either are not available in this study. Of the two, the net hydrograph is easier of derivation, the sole question being how much of the recorded

hydrograph should be taken as base-flow and how should this base-flow hydrograph be drawn. Fortunately, the base-flow hydrograph, if taken within reason, can form only a small portion of the total volume in this type of summer flood. Thus the net hydrograph and the corresponding flood runoff-value can be closely approximated. Similarly, errors in the assumed base-flow hydrograph will be least felt in the few intervals of largest discharge that give the key- or peak-values in the distribution-graph. Hence in these studies, the base-flow hydrograph was drawn as a straight line from the first hour after the hydrograph began to rise to some point where the hydrograph is decreasing slowly. This straight-line interpretation may be questioned but

Fig. 1--Pemigewasset River Basin

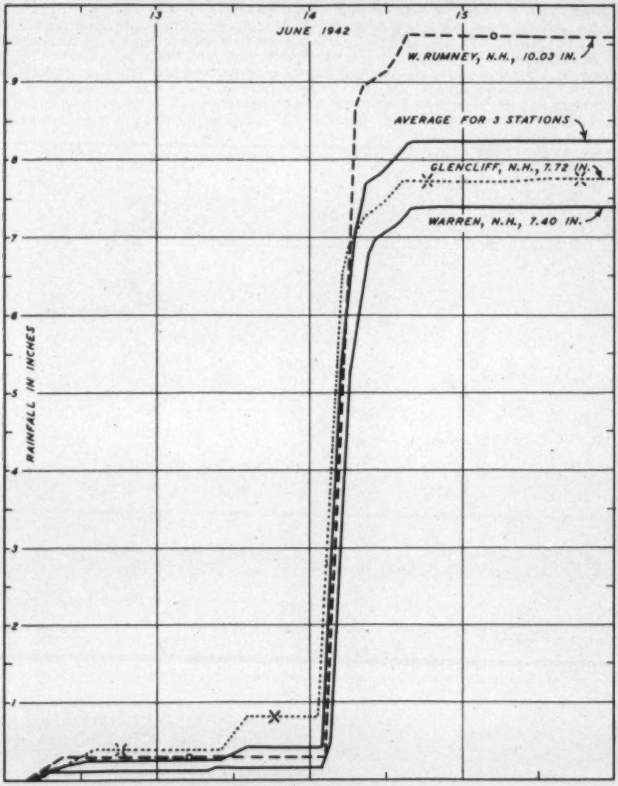


Fig. 2--Mass-curves of rainfall, storm of June, 1942, for Baker River Basin above Wentworth, New Hampshire

appeared as good as any and could be reproduced and computed easily. The volume remaining after deducting the flood runoff-volume from the total rainfall-volume over the area, was considered as infiltration and other losses to the flood-runoff. The value so obtained is believed more accurate than the basic rainfall-values. The more serious question is the method of distributing this volume lost to runoff in deducting it from the recorded pluviograph to obtain the period-runoff values used in determining the distribution-values. Again the method used was that most easily reproduced and computed in view of the fact that no data are available on this phase of the study and the pertinent rainfall-periods are very short. The effect on the resulting distribution-values for different assumptions in deducting the amount lost to runoff should be recognized. (Ordinarily the rate of such losses is assumed to decrease with progress of the storm.) For example, take a storm of two significant runoff-periods similar to the ones in this study. Assuming a uniform

Table 1--Distribution-values at 3-hour intervals, Baker River at Wentworth, New Hampshire, storm of June 14-15, 1942

Basic data [Cols. (1) - (4)], determination distribution-values [Cols. (4) - (8)]								Reproduction of hydrograph from distribution-values and basic data						Results of computations assuming first period runoff twice that of second				
Rainfall		Flood-runoff				Distr.-value, computed	Interval No.	Flood-runoff				Base-flow	Total hydrograph	Flood-runoff			Distr.-value, computed	Reproduced net hydr.
			Net hydrograph					Value equal to 8×dsf	Net hydrograph					See note e	Net-hydrograph[d]			
3-hr period (1)	Am't (2)	Loss =0.45 in/hr (3)	Recorded (4)	2nd period[b] (5)	1st period[c] (6)	(7)	(8)	(9)	1st period (10)	2nd period (11)	Both periods (12)	(13)	(14)	(15)	2nd period (16)	1st period (17)	(18)	(19)
h	in	in	cfs	cfs	cfs	pct		cfs	cfs	cfs	cfs	cfs	cfs	in	cfs	cfs	pct	cfs
15	0.3	0.00	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
18	4.8	3.46	2758	0[a]	2746	6.2	1	43910	2722	...	2722	54	2776	2.54	...	2758	8.6	2770
21	1.7	0.35	9032	278	8754	20.0	2	4440	8782	275	9057	62	9119	1.27	1379[a]	7658	23.8	9060
24	0.4	...	10683	886	9797	22.3	3	...	9792	888	10680	70	10750	...	3829	6854	21.3	10700
03	0.2	...	7813	991[a]	6760	15.4	4	...	6762	990	7752	79	7831	...	3427	4386	13.7	7820
06	0.1	...	5403	683	4720	10.8	5	...	4742	684	5426	87	5513	...	2193	3210	10.0	5420
			3658	477	3181	7.3	6	...	3205	480	3685	95	3780	...	1605[a]	1996	6.2	3610
			2252	320[a]	1959	4.5	7	...	1976	324	2300	104	2404	...	998	1254	3.9	2260
			1277	198	1079	2.5	8	...	1098	200	1298	112	1410	...	627	650	2.0	1270
			895	109	786	1.8	9	...	790	111	901	120	1021	...	325	570	1.8	902
			673	79.5[a]	612	1.4	10	...	615	80	695	128	823	...	285	388	1.2	677
			570	62	508	1.2	11	...	527	62	589	136	725	...	194	376	1.2	580
			508	51.4[a]	450	1.0	12	...	439	53	492	145	637	...	188	320	1.0	515
			432	45.5	386.5	0.9	13	...	395	44	439	153	592	...	160[a]	284	0.9	451
			378	39.1	338.9	0.8	14	...	351	40	391	161	552	...	142	236	0.7	371
			332	34.3	297.7	0.7	15	...	307	36	343	170	513	...	118	214	0.7	339
			287	30.1	256.9	0.6	16	...	263	31	294	178	472	...	107	180	0.6	308
			233	26.0	207.0	0.5	17	...	220	27	247	186	433	...	90[a]	138	0.4	226
			185	21.0	164.0	0.4	18	...	176	22	198	194	392	...	69	116	0.4	194
			168	16.6	151.4	0.3	19	...	132	18	150	202	352	...	58[a]	106	0.3	162
			153	15.3	137.7	0.3	20	...	132	13	145	211	356	...	53	100	0.3	145
			142	13.9	128.1	0.3	21	...	132	13	145	219	364	...	50[a]	90	0.3	145
			133	13.0	120.0	0.3	22	...	132	13	145	227	372	...	45	88	0.3	145
			114	12.2	101.8	0.2	23	...	88	13	101	236	337	...	44	70	0.2	112
			86	10.3	75.7	0.2	24	...	88	9	97	244	341	...	35[a]	48	0.1	64
			56	7.7	48.3	0.1	25	...	44	9	53	252	305	...	24	32	0.1	48
			26	4.9	21.1	...	26	...	...	4	4	260	264	...	16	10	...	26
			2.1	2.1	....	...	27	...	...	...	...	269	269	...	5[a]	...	...	5
Totals	7.5	3.81	48249.1	4426.9	43787.1	100.0	27	48350	43910	4439	48349	4354	52703	3.81	16076	32132	100.0	48323

[a]Adjusted values. [b](0.35/0.35) = 1.00. [c](3.46/0.35) = 9.88. [d]Recorded same as Column (4). [e]Loss taken to make first period runoff = 2.54 inches, second = 1.27 inches.

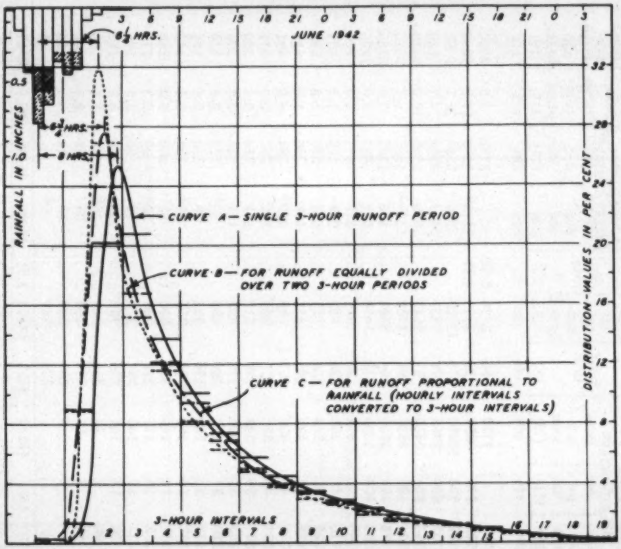

JUNE 1942
6½ HRS.
6¾ HRS.
8 HRS.
RAINFALL IN INCHES
0.5
1.0
CURVE A — SINGLE 3-HOUR RUNOFF PERIOD
CURVE B — FOR RUNOFF EQUALLY DIVIDED OVER TWO 3-HOUR PERIODS
CURVE C — FOR RUNOFF PROPORTIONAL TO RAINFALL (HOURLY INTERVALS CONVERTED TO 3-HOUR INTERVALS)
DISTRIBUTION-VALUES IN PER CENT
3-HOUR INTERVALS

Fig. 3--Comparison of distribution-values for different assumed rates of runoff-losses

infiltration-rate, if it results in greater extremes in the pluviograph runoff-values for the adjacent periods, will give peak-distribution values smaller than those obtained from an assumption of infiltration or loss to runoff-rates resulting in the two runoff-periods being more nearly equal in value. This effect on the distribution-values is shown in Figure 3. Curve A is for one extreme where the first of two periods has 0.58-inch runoff, the second period none, and the peak-distribution values are less than those shown for Curve B where the runoff is equal for both periods. Curve C was obtained by computing distribution-values for hourly intervals (see Table 2 for computations), converted to three-hour intervals, for this comparison, and assuming runoff proportional to rainfall. The runoff in this case was about 50 per cent greater for the first period than for the second period, and Curve C lies between Curves A and B similar to the runoff-assumption. Hence distribution-values based on runoff-assumptions as for Curve A will be less conservative than those for Curve B in evaluating maximum floods (see also Table 1).

(8) The foregoing limitations are inherent in any determination of distribution-values. The method to be described for computing these values does not overcome these limitations. The following method is applied to a flood-hydrograph of two runoff-periods and is the simplest case of multiple-period runoff. It serves to illustrate the procedure. The method is probably not original to these studies. It is merely reversing the procedure used normally to constitute a flood-hydrograph from the distribution-values and the period-runoff values given by the assigned pluviograph. Since the rising side of the hydrograph reflects not only basin-characteristics but also the chance-distribution in time of the flood-producing rainfall, the decreasing limb of the hydrograph is used for the computation. The period-runoff values from the recorded pluviograph and the runoff for each interval of the hydrograph are obtained and tabulated. Keeping in mind the proportion contributed by each of the runoff-periods and their relative position in the tabulation of runoff-intervals from the hydrograph, the computations are carried through by trial and error. The example used is for the Baker River at Wentworth, New Hampshire. The computations are shown in tabular form in Table 1. The pluviograph and hydrographs are shown in Figure 5. Referring to Table 1,

Table for Figure 3

Time ending	Rainfall	Curve A Runoff	Curve A Distribution	No. 3-hr int.	Curve B Runoff	Curve B Distribution	Curve C Runoff	Curve C Distribution
h	in	in	pct		in	pct	in	pct
15								
16	.01							
17	.15							
18	.43							
19	.78							
20	.65	.58			.29		.341	
21	.36		0.0					0.4
22	.45							
23	.41	0			.29		.224	
24	.08		1.4	1		8.9		9.0
01	.04							
02	.01	0						
03	.01		20.2	2		26.9		24.0
04	.01							
05								
06			20.8	3		15.2		16.8
09			13.7	4		11.6		12.1
12			10.1	5		8.3		9.4
15			7.4	6		6.3		6.9
18			5.8	7		5.0		4.8
21			4.5	8		3.8		4.0
24			3.5	9		3.0		3.5
03			2.9	10		2.6		2.7
06			2.4	11		2.1		1.9
09			1.9	12		1.6		1.4
12			1.5	13		1.3		1.2
15			1.2	14		1.2		1.0
18			1.0	15		0.8		1.0
21			0.7	16		0.6		
24			0.5	17		0.4		
03			0.3	18		0.2		
06			0.2	19		0.2		

cognizance is had of the data in Column (3) showing the runoff from the first period as 9.88 times that for the second period. This relation is applied in Columns (5) and (6) such that the average discharge-value of an interval in Column (6) is about 9.88 times that of the interval on the following line in Column (5) and the average discharge-value for a given interval as shown in Column (6) when added to the value for the interval on the same line in Column (5) gives approximately the discharge-value for that interval recorded in Column (4). The distribution-values are then computed by dividing the value for each interval in either Column (5) or Column (6) by the total of the column used and the values expressed in per cent [Column (7)]. The procedure in this type of computation has usually been to start the computation at the very end of the net hydrograph where the last interval represented the last period of runoff alone so that the last distribution-value could be computed directly. However, a start at the end of the hydrograph dealt with very small values, subject to considerable error in reading, and more trials. A start made in some reach midway of the decreasing limb of the hydrograph where values are large and easily read will be found to advantage. Computations can be carried in both directions, or a fresh start made to prevent carrying forward slight errors that tend to magnify. For suitable hydrographs the number of trial-determinations were found surprisingly small. Reconstitution of the hydrograph is shown in Columns (9) to (14) and requires no explanation. The tabular form is set up for greatest ease in computation of the distribution-values and for reconstituting the hydrograph as a check. Results of computations assuming values of runoff as in Column (15) are shown in Columns (16) to (19).

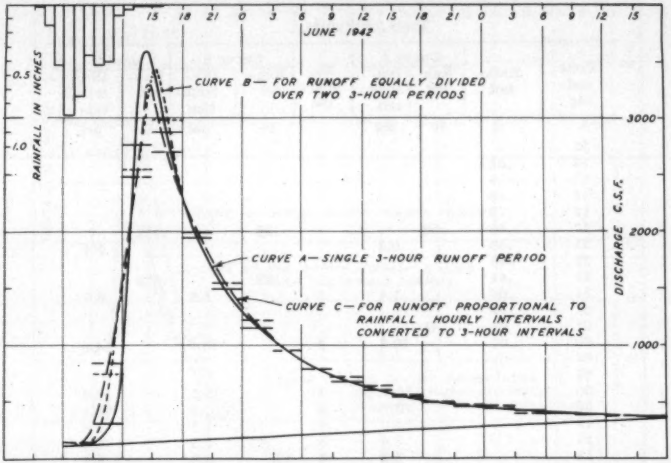

15 18 21 0 3 6 9 12 15 18 21 0 3 6 9 12 15
JUNE 1942
RAINFALL IN INCHES
0.5
1.0
CURVE B— FOR RUNOFF EQUALLY DIVIDED OVER TWO 3-HOUR PERIODS
CURVE A— SINGLE 3-HOUR RUNOFF PERIOD
CURVE C— FOR RUNOFF PROPORTIONAL TO RAINFALL HOURLY INTERVALS CONVERTED TO 3-HOUR INTERVALS
DISCHARGE C.S.F.
3000
2000
1000

Fig. 4--Comparison of reconstituted hydrographs for different assumed rates of runoff-losses

(9) If the computation of distribution-values is carried beyond the peak into those intervals comprising the rising side of the hydrograph and use of these values shows close agreement with the recorded hydrograph, it would appear that assumptions of infiltration-rates and resulting runoff-distribution approached that for the actual because the rising side of the hydrograph reflects runoff-distribution as well as basin characteristics. Referring to Figure 4, in using the initial distribution-values of Curves B and C, it was impossible to reconstitute the rising limb of the hydrograph, yet both sets of values in Table 1 check the recorded hydrograph. Before any definite conclusion can be reached it will be necessary to obtain several hydrographs at each station generated by rainfall with different period-distribution. And before exhausting the available data on the floods of June, 1942, it is possible that further computations of hourly or bihourly values may yield interesting, if not valuable, information on the characteristics of the distribution-graph. As far as practical use of the distribution-values is concerned, the periods used are considered amply short in duration and easier of computation. In connection with application of the distribution-values, the time-interval between center of time of the first runoff-period to that for the first hydrograph-interval is indicated in Figure 6. This is of value when it is required to combine synthetic hydrographs and the time-element is important.

(10) The increasing variety of types of streams for which distribution-values are available has encouraged the attempt to classify such streams on their primary physical characteristics, particularly such physical characteristics as those readily obtainable from topographic maps of the basin. The objective of this classification is an attempt to increase the assurance with which available distribution-graph data may be applied to such streams lacking this data but having comparable physical characteristics. To evaluate the majority of the physical characteristics and attempt a composite picture from them is too involved and may get into assumptions and approximations that would defeat the primary purpose of such an index. A part of these imponderables will be cancelled in limiting the comparison to areas in the same portions of a river-basin or adjacent regions where runoff-conditions, slopes, and valley-storage, or lack of it, are much the same. Comparisons, therefore, should be attempted only between areas in the same territory with like terrain-conditions and of like size.

(11) As previously stated, obtaining the peak-value to be expected from a given stream has been a major incentive in these studies. The peak of the hydrograph with its magnitude and time of occurrence, is the index to the flood-runoff characteristics of primary interest. The physical

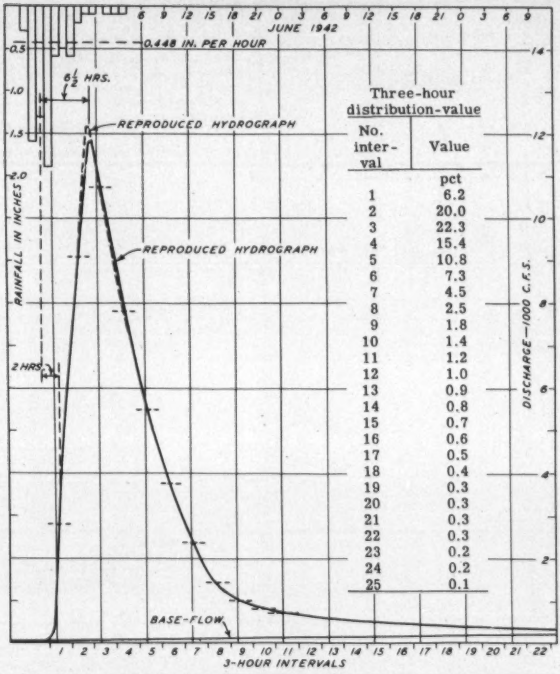
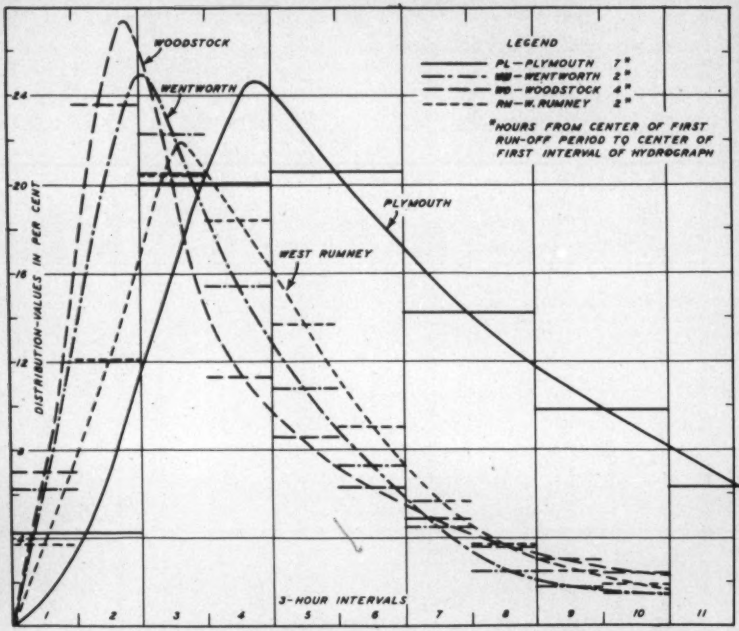


Fig. 5--Distribution-values, hydrograph and pluviograph, Baker River at Wentworth, New Hampshire, flood of June, 1942

characteristic used here takes cognizance of this fact and that, under ordinary rainfall-conditions, all streams may be considered to have a "flood-peak" producing area depending on the drainage-area distribution relative to distance from the discharge-point. The most remote areas from which flood-flows arrive after that from the main concentration of area will not add to the peak-flow (see Fig. 7, Nubanusit Brook areal distribution-curve beyond Mile 10). Similarly, those areas downstream from the peak-producing area will pass their peak-flow before arrival of that from the main concentration of area and will affect the peak-flow only in so far as the volume tends to fill in the available channel-storage in the reach between the tributary inflow and main-stem outflow-point under consideration. Hence, in comparing the distribution-values for two streams, it may be assumed that the stream with the greater concentration of tributary area would produce the greater peak-flow, that the distance of the greatest areal concentration from the discharge-point would indicate the relative time of the main peak-arrival, that for streams in similar terrain the more nearly alike the magnitude and position of the areal concentration of the two streams under comparison the more valid the comparison. These general considerations are discussed later in connection with application to flood-studies. The areal distribution and its probable effect can be determined in a general way from the stream-pattern but visual comparison of two stream-patterns is difficult because of the variation in detail. Therefore, the concentration of area represented by a graph showing increments of area against miles distance from the discharge-point is desirable.



No. int.	Distribution-values for interval 3 - hour WD	WN	RM	6 - hour PL	No. int.	Distribution-values for interval 3 - hour WD	WN	RM	6 - hour PL
	pct	pct	pct	pct		pct	pct	pct	pct
1	7.0	6.2	3.7	4.2	15	0.9	0.7	0.7	1.3
2	23.6	20.0	12.1	20.1	16	0.6	0.6	0.6	1.2
3	20.5	22.3	20.5	20.6	17	0.4	0.5	0.5	1.1
4	11.5	15.4	18.4	14.2	18	0.3	0.4	0.4	0.9
5	8.6	10.8	13.7	9.8	19	0.2	0.3	0.4	0.8
6	6.3	7.3	9.1	6.3	20	0.1	0.3	0.3	0.7
7	4.9	4.5	5.7	3.9	21	....	0.3	0.3	0.5
8	3.6	2.5	3.7	2.9	22	....	0.3	0.3	0.4
9	3.0	1.8	2.5	2.3	23	....	0.2	0.2	0.3
10	2.4	1.4	1.8	2.0	24	....	0.2	0.2	0.1
11	2.0	1.2	1.4	1.8	25	....	0.1	0.2	0.1
12	1.6	1.0	1.2	1.6	26	....	....	0.1	....
13	1.4	0.9	1.0	1.5	27	....	....	0.1	....
14	1.1	0.8	0.9	1.4	D-A acres	193	59	143	622

Fig. 6--Distribution-values for streams in Pemigewasset River-Basin, based on flood of June, 1942

To obtain such a curve, the mileage along the main stem and along the principal tributaries is stepped off. Fairly careful delineation is made of these increments of area between each mile or distance-interval. In the determination, the partial areas for a given distance-interval are shown by a given color to prevent confusion and facilitate the work. Increments of area between contiguous mile-points are summed up and a curve drawn showing increment of area versus distance in miles from the outflow-point.

(12) Obviously, the areal distribution-curve does not evaluate stream-slopes and channel-storage. In the streams under consideration in these studies, channel-storage is relatively small, and of these two items slope is considered the predominant influence. Hence, a representation of slope is used as the second criteria for comparing two streams. In representing the slope-criteria, the distance-elevation curve or profile of the stream-channels is drawn for the main stem and the major tributaries. The data are obtained from topographic maps using the same distance-points as laid off for the areal distribution-curve. The profiles of the streams under comparison are drawn and superimposed one on the other so that visual comparison may be made. An example of this is shown in Figure 7.

(13) Figure 7 is a complete picture of the method comparing areal distribution and slope of the Nubanusit Brook for which distribution-values were required and South Branch Ashuelot for which distribution-values were available. This comparison, it should be noted, did not evaluate the required distribution-values. It did determine that a larger flood-peak would be indicated in using the available South Branch Ashuelot distribution-values than are to be expected from actual Nubanusit River distribution-values.

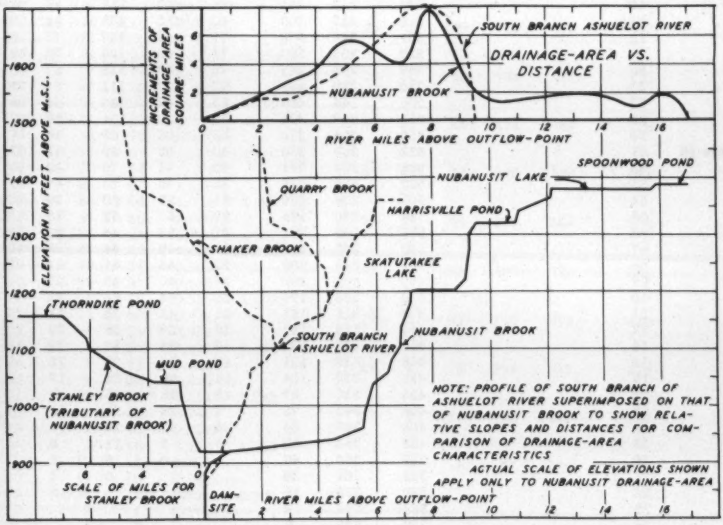

SOUTH BRANCH ASHUELOT RIVER
DRAINAGE-AREA VS. DISTANCE
NUBANUSIT BROOK
INCREMENTS OF DRAINAGE-AREA SQUARE MILES
RIVER MILES ABOVE OUTFLOW-POINT
ELEVATION IN FEET ABOVE M.S.L.
SPOONWOOD POND
NUBANUSIT LAKE
QUARRY BROOK
HARRISVILLE POND
SHAKER BROOK
SKATUTAKEE LAKE
THORNDIKE POND
SOUTH BRANCH ASHUELOT RIVER
NUBANUSIT BROOK
MUD POND
STANLEY BROOK (TRIBUTARY OF NUBANUSIT BROOK)
NOTE: PROFILE OF SOUTH BRANCH OF ASHUELOT RIVER SUPERIMPOSED ON THAT OF NUBANUSIT BROOK TO SHOW RELATIVE SLOPES AND DISTANCES FOR COMPARISON OF DRAINAGE-AREA CHARACTERISTICS
ACTUAL SCALE OF ELEVATIONS SHOWN APPLY ONLY TO NUBANUSIT DRAINAGE-AREA
SCALE OF MILES FOR STANLEY BROOK
DAM-SITE
RIVER MILES ABOVE OUTFLOW-POINT

Fig. 7--Comparison of drainage-basin characteristics, Nubanusit River

Table 2--Computation of distribution-values, hourly and 3-hour intervals, storm

Date	Time	Rain-fall	Runoff		Total hydro-graph	Base-flow	Net hydro-graph	0.43 1.048	0.78 1.900	0.65 1.584	0.36 0.877
1942	h	in	in	dsf							
June 14	18	0.43	.079	221	101	100	1	1	...	...	...
	19	0.78	.143	400	107	105	2	10	2	...	...
	20	0.65	.119	334	116	110	6	42	19	2	...
	21	0.36	.066	185	132	115	17	105	76	16	1
	22	0.45	.083	231	178	120	58	315	190	64	9
	23	0.41	.075	210	350	126	224	525	570	158	35
	24				996	131	865	525	950	475	81
June 15	01				2460	136	2324	432	950	792	263
	02				3530	141	3389	368	781	792	438
	03				3460	146	3314	314	665	652	438
	04				3060	152	2908	278	570	555	361
	05				2650	157	2493	252	504	475	307
	06				2330	162	2168	233	456	420	263
	07				2060	167	1893	216	422	381	233
	08				1840	172	1668	199	392	351	211
	09				1680	177	1503	182	361	327	195
	10				1540	182	1358	166	331	301	181
	11				1420	188	1232	149	300	276	167
	12				1300	193	1107	132	270	250	153
	13				1200	198	1002	115	240	225	137
	14				1120	203	917	101	205	200	125
	15				1040	208	832	89	182	174	111
	16				984	213	771	84	162	152	97
	17				918	218	700	80	152	135	84
	18				861	223	638	77	144	127	75
	19				820	228	592	74	139	120	70
	20				780	233	547	70	133	116	67
	21				730	238	492	67	127	111	64
	22				700	244	456	63	122	106	61
	23				670	249	421	59	114	101	59
	24				650	254	396	53	106	95	56
June 16	01				623	259	364	46	95	89	53
	02				605	264	341	40	84	79	49
	03				587	269	318	35	72	70	44
	04				560	274	286	31	63	60	39
	05				544	280	264	29	57	52	33
	06				536	285	251	27	53	48	29
	07				520	290	230	26	49	44	26
	08				504	295	209	25	48	41	24
	09				492	300	192	24	46	40	23
	10				480	306	174	23	44	38	22
	11				472	311	161	21	42	36	21
	12				464	316	148	20	38	35	20
	13				456	321	135	19	36	32	19
	14				448	327	121	17	34	30	18
	15				436	332	104	14	30	28	17
	16				424	337	87	10	25	25	16
	17				416	343	73	7	19	21	14
	18				408	348	60	4	13	16	11
	19				403	353	50	0	8	11	9
	20				398	358	40	...	0	6	6
	21				393	364	29	...	...	0	4
	22				388	369	19	...	...	...	0
	23				383	374	9	...	...	...	...
	24				379	379	0	...	...	...	...
Totals		3.08	.565	1581	...	...	37956[a]	...	...	...	...

[a](37956/24)=1582 day-second-feet=0.565 inch. [b]Increased to basis 0.58-inch runoff.

of June 14-15, 1942, East Branch Pemigewasset River, Lincoln, New Hampshire

0.45	0.41	0.41	Distri.-values		Run-	Period		Hydrograph			
1.098	1.000	adj.	Derived 1-hr	Computed 3-hr	off	1	2	Net		Total	Adjusted[b]
					dsf			dsf	cfs	cfs	cfs
...	1	...									
...	- 10	...									
...	- 57	...			955	4		4	32	137	141
...	- 181	...									
1	- 521	...									
11	-1075	1	0.018		626	86	2	88	704	824	844
44	-1217	10	0.181								
110	- 223	40	0.724	0.380							
330	680	100	1.810			229	56	285	2280	2416	2480
550	695	300	5.432								
550	594	500	9.053	8.992							
452	503	500	9.053			160	150	310	2480	2632	2700
384	412	412	7.460								
330	311	350	6.337	23.985							
291	224	300	5.432			116	105	221	1768	1935	1990
264	174	265	4.798								
244	135	240	4.345	16.790							
226	114	222	4.020			90	76	166	1328	1510	1550
208	94	206	3.730								
191	94	190	3.440	12.149							
173	113	174	3.150			66	59	125	1000	1198	1233
156	120	158	2.861								
138	138	142	2.571	9.451							
121	128	126	2.281			46	43	89	712	925	953
105	123	110	1.992								
93	96	96	1.738	6.850							
88	73	85	1.539			38	30	68	544	772	795
83	40	80	1.448								
80	24	76	1.376	4.786							
77	11	73	1.322			33	25	58	464	708	729
73	13	70	1.267								
70	11	67	1.213	3.971							
66	23	64	1.159			26	21	47	376	635	654
62	35	60	1.086								
55	38	56	1.014	3.452							
48	45	50	0.905			18	17	35	280	554	570
42	52	44	0.797								
36	49	38	0.688	2.703							
33	38	33	0.598			13	12	25	200	490	504
30	29	30	0.543								
28	19	28	0.507	1.853							
27	14	26	0.471			12	9	21	168	474	488
26	9	25	0.453								
25	4	24	0.435	1.437							
24	2	23	0.416			10	8	18	144	465	479
22	7	22	0.398								
21	10	20	0.362	1.243							
20	8	19	0.344			7	6	13	104	441	454
18	2	18	0.326								
14	8	16	0.290	1.032							
11	17	13	0.235				4	4	32	385	397
8	17	10	0.181								
4	15	7	0.127	0.700							
0	9	4	0.072								
...	0	0	....								
...	....	5523	99.988	....	...	...	...	...	...	...	...

(14) For a tributary stream under study, where closer approximation to time of peak-arrival and general hydrograph-shape is desired for correlating it with other tributary inflows, then an attempt is made to bracket the stream under consideration between two streams, one with physical characteristics tending to produce more severe floods and one with characteristics to produce less severe floods. In the initial comparison, emphasis is placed on areal distribution as shown in Figure 8 for the Beards Brook comparison. Stream-profile patterns are then superimposed as shown in Figure 9 for the Beards Brook profile-comparison. Some adjustments then are made between the distribution-graphs of the streams bracketing the one with unknown distribution-values, based on judgment and appraisal of the areas under consideration.

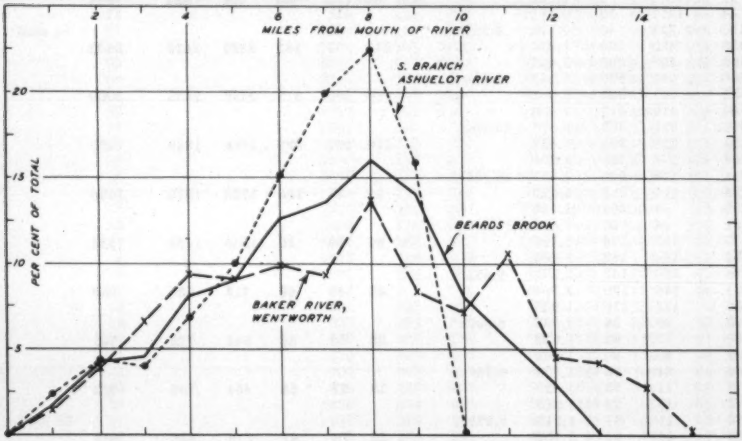


Fig. 8--Comparison of areal distribution, Beards Brook

(15) The general considerations based on areal distribution are believed of special interest. Following is an example to more readily permit visualizing this characteristic for study of hydrographs and its importance as a basic concept in studies on reduction of flood-peaks by reservoirs. Consider the discharge-hydrograph to be expected at the end of a long trough with uniform channel-section and slope, and having a short apron along one side shaped to receive and uniformly distribute into the trough-water from six buckets dumped simultaneously onto the apron. The hydrograph shown at the discharge end of the trough would have a maximum length in time about equal to the time required for the water to traverse the length of the trough; it would not have any peak-value but have practically equal discharge-ordinates. Compare this with the hydrograph to be expected if the same trough were cut into six equal lengths each set on the same slope as the single long trough but arranged radially as the spokes of a wheel to discharge at the center-point or hub. The discharge-hydrograph in this case would be only about one-sixth as long, and have discharge-ordinates about six times as large as the hydrograph for the single long trough. Similarly the curve representing the areal distribution relative to distance from the discharge-point in the first case would have short uniform ordinates and the maximum abscissa representing about the length of the trough; whereas the curve in the second case would have ordinates about six times as long and a maximum abscissa about one-sixth as long as in the first case. Therefore, the respective discharge-time curve or hydrograph (for single-period runoff) and the area-distance curve or areal distribution-curve would be similar in shape. The direct relationship of the coordinate values for the two types of curves further emphasize the comparison. The ordinate of the flow-graph represents a volume. This volume is a direct function of the drainage-area represented by ordinates in the area-curve. In fact, the volume of flow may be derived from drainage-area values multiplied by the runoff-values and the coefficient required to express the volume in the chosen units. The abscissa of the flow-graph is time and gives the time of arrival of the given

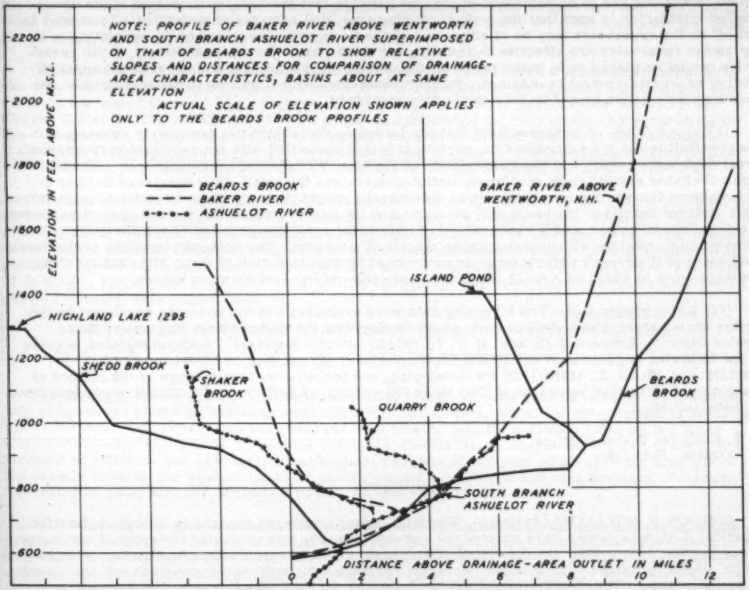


Fig. 9--Comparison of stream-profiles, Beards Brook

discharge-volume at the measuring-point; the abscissa of the area-graph is the distance an area contributing discharge-volume is from the measuring-point. A correlation of these two sets of curves to give the time of travel and discharge-volume from the contributing areas would result in a hydrograph of discharge but is impracticable because of the unknown effects of slopes and channel-storage. Hence the modifications to application of the area-distance curve to choosing distribution-values by consideration of slope and channel-storage.

(16) The use of the areal distribution-concept in evaluating reservoir-possibilities for controlling floods in a given basin is apparent from the following consideration. For a stream with characteristics comparable to the long trough, some reservoir-control would be required on each one of the tributaries to reduce the outflow-peak. It is apparent that shutting off one of the tributary inflows (equivalent to one of the buckets of water in the example) would not materially reduce the outlet flood-peak if the tributaries are cut off at the upper end or middle of the basin. The hydrograph for the first case would merely be shorter in time, that for the second case would show a dip; in both cases no material reduction would be obtained in the peak-flow value. However, some reduction would be obtained in the peak-outflow if the lowest tributaries were cut off because the main-stem channel-storage would not be filled initially by the lower tributaries and would thus be available for containing some of the upper tributary inflow. Contrast this with a stream-basin area comparable to the multiple-trough example. Here cutting off any one of the tributaries (analogous to one of the buckets of water) would reduce the flood-peak in direct proportion. This is the type of stream-basin areal distribution most profitable for reservoir-control. Most streams are of a type between these extremes. When reservoir-control is proposed for the ordinary streams, careful study should be made of the areal distribution of the basin-tributaries remaining uncontrolled, particularly where reservoirs are proposed on the tributaries furthest from the point for

which reductions are to be provided. It may be possible that the areal distribution of the uncontrolled tributaries is such that the peak-producing area still remains uncontrolled. Then what is cut off by the reservoirs may be at either end of the flood-hydrograph and be disappointing in so far as the reservoirs are effective in reducing the flood-peak. Or more positively, if the reservoirs can be so placed as to make the resulting uncontrolled area long and narrow, the most effective reservoir-control is obtained. Further reservoir-control will be found unprofitable and recourse may better be had to local protective measures.

(17) Conclusion--It is appreciated that the foregoing discussion has not nearly exhausted the possibilities in the available data, particularly that connected with the recorded hydrographs, areal distribution-data, and the interrelation of the two. The discussion is primarily intended to make available results from studies on distribution-values for small drainage-areas in hilly to mountainous terrain obtained from actual data usually adaptable to the determination of such values. This includes details of the basic data available and its interpretation, the method applied to derive the distribution-values, and a ready means of comparing available physical characteristics of two streams in connection with applying known distribution-values. The concept regarding preliminary evaluation of flood-peak reductions to be anticipated by consideration of areal distribution of the drainage-area is added as a most important application of the studies made herein.

(18) Acknowledgments--The foregoing data were evaluated and the concepts developed by the writer during river-basin studies made as an employee of the United States Engineer Office, Boston District, Lieutenant-Colonel H. P. DUNBAR, District Engineer. Acknowledgment is given to the following employees of the United States Engineer Office, Boston District: ELLIOT F. CHILDS and FRED. C. MERRIKIN for developing, and initially working through of the method of computing distribution-values as well as their aid and that of EMILY L. PEASLEE in computations of these values.

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DISCUSSION

GORDON R. WILLIAMS (Arlington, Virginia)--Many engineers engaged in runoff-studies for practical design-problems have adopted the unit-hydrograph, with ordinates in terms of discharge at any instant, rather than use the distribution-graph, which is essentially a histogram, or bar-graph, whose ordinates represent the percentage of the total runoff which occurs in any incremental period of time. The distribution-graph can be converted to a smooth graph, but the ordinates at any instant have no significance. In this paper, the author apparently finds the distribution-graph more convenient than the unit-hydrograph in carrying out his methodology.

The first half of the paper deals with the derivation of distribution-graphs from hydrographs resulting from storms having several periods of unequal rainfall. Such a process is usually one of trial and error with far from satisfactory results. The author's method of working backwards the usual computation of deriving hydrographs from several periods of rainfall-excess and a distribution-graph has received consideration by other engineers, with some variations in detail, but as far as the writer knows the method has never been presented before in any published article.

As the author readily admits, the distribution-graph values vary considerably with the assumptions regarding the distribution of the infiltration and other losses. A number of widely different assumptions are mathematically possible (although some may be hydrologically illogical), as shown in the example for the East Branch of the Pemigewasset River near Lincoln, New Hampshire (see Fig. 3) where the rainfall-excess or storm-runoff is only 18 per cent of the storm-rainfall. Experience to date indicates that the most logical assumption is to assume a high initial loss in the first rainfall-periods, followed by much smaller and relatively uniform loss for the remainder of the storm. The writer utilized the data in Table 2 to derive a distribution-graph using the above-mentioned assumption. It was assumed that there was an initial loss of 1.86 inches or, in other words, there was no surface-runoff prior to 20^{h}, June 14. The remaining loss of 0.65 was uniformly distributed throughout the next three-hour period. The recorded net hydrograph shown in Column (7), Table 2, can then be considered a three-hour distribution-graph (after proper conversion). When converted to averages for three-hour periods the first six ordinates, expressed as percentages, are 0.79, 17.3, 23.0, 15.1, 10.8, and 8.0. For this distribution-graph the time from the center of the first period of rainfall-excess to the peak of the graph is 5-1/2 hours which is shorter than any of the corresponding times shown on Figure 3. When used with a hypothetical storm, this distribution-graph would give a more concentrated flood-hydrograph than any of the

curves shown on Figure 3. It should be emphasized that distribution-graphs derived from a single flood cannot be depended on to represent basin-characteristics under all conditions and they should be checked, if possible, by other derivations.

The reconstituted flood-hydrographs shown in Figure 4 tend to give a misinterpretation as to the effect of the distribution-graphs in Figure 3. For example, the reconstituted hydrograph derived by the use of Curve A has a higher peak-discharge than those hydrographs derived from Curves B and C. The reconstituted hydrographs are dependent not only on the characteristics of the distribution-graph but also on the assumptions regarding the distribution of rainfall-excess. If Curve A is used in connection with a hypothetical storm-pattern it will produce a hydrograph with a smaller peak-discharge than will be obtained by the use of either Curve B or Curve C.

The last part of the paper is devoted to methods of showing graphically the inter-relationships of the drainage-basin characteristics of length, slope, and areal distribution. Only the relative effect of these relationships on the distribution-graphs is considered and, therefore, their usefulness is quite limited. Other investigators have had considerable success in setting up empirical relations between drainage-basin characteristics and unit-hydrograph characteristics. The work of SNYDER, McCARTHY, MORGAN, and HULLINGHORST along these lines is already well-known and is receiving wide application.

ESTIMATION OF STREAM-FLOW FROM ALKALINITY-DETERMINATIONS

Arno T. Lenz and Clair N. Sawyer

Introduction--Occasionally the engineer making stream-measurements is required to obtain data at locations where conventional methods are of little value. Such was the problem of Madison Lakes Survey. This Survey has been charged with determining the pollution entering the lakes from the Nine Springs Sewage Treatment Plant, the Yahara River, and several small creeks (Fig.1). Strength of pollution was determined by chemical analysis of samples which gave the strength of the sample in parts per million (ppm) or pounds per million pounds and measurement of stream-flow rates in cubic feet per second or pounds per period of time.

Unfortunately the measurement of stream-flow was complicated by the fact that the drainage-basins of the tributary streams are generally low at the outlets, often marshy and are subject to backwater from the lakes for a considerable distance up from the mouth. Starkweather Creek, for example, has low land at almost lake-level for three miles up from the mouth while the entire length of the drainage-area is but six miles. A gage located beyond the backwater-effect would measure the runoff from less than half the creek-basin. One located near the mouth would be affected so much by backwater as to make an ordinary rating-curve useless. For example, on February 23, Nine Springs Creek had a discharge of 37.4 sec-ft. On August 6 the gage-height had risen 0.08 foot but the measured discharge had decreased to 4.8 sec-ft because the lake-level control had risen 0.73 foot. PARSHALL or other flumes to be effective would have had to raise the ground-water level at least a foot. This would have disturbed natural runoff-quantities and been otherwise inexpedient.

It was decided therefore to constrict the flow at the measuring-stations to a narrow channel with board side-walls and natural bottom. Velocities in this "flume" were measurable even during low flow-periods. Current-meter measurements were then made at rather frequent intervals; 49 were made in 52 weeks on Nine Springs Creek. At the same time samples were taken for chemical analysis, and it became evident that during flood-periods the alkalinity of the water decreased markedly. This is logical as the soil is generally of a residual limestone character and the ground-water has an alkalinity of about 300 ppm. On the other hand the rain-water has no dissolved salts. The greater the amount of surface-runoff, the less the alkalinity of the mixture.

Alkalinity-discharge rating-curves--A logarithmic plotting showed that alkalinity was a function of discharge. Since this relationship should be independent of the size of the area, the discharge per square mile is plotted with alkalinity on Figure 2. The combined data for eight streams was in sufficient agreement to determine the shape of the curve which was then used as a pattern and moved around to best fit the data so that a separate curve could be drawn for each individual stream.

It will be noted there are two distinct parts to the curve. For flows greater than 0.8 sec-ft per square mile (flood-runoff) the alkalinity decreases rapidly with increased runoff. At flows less than 0.8 sec-ft per square mile (ground-water runoff) the slope of the curve is very flat.

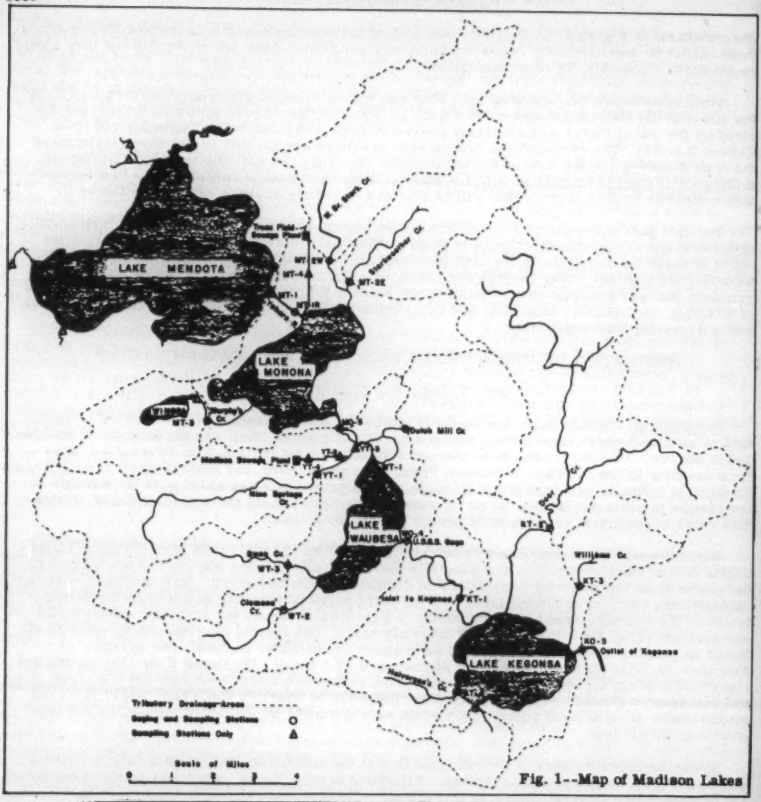

Fig. 1--Map of Madison Lakes

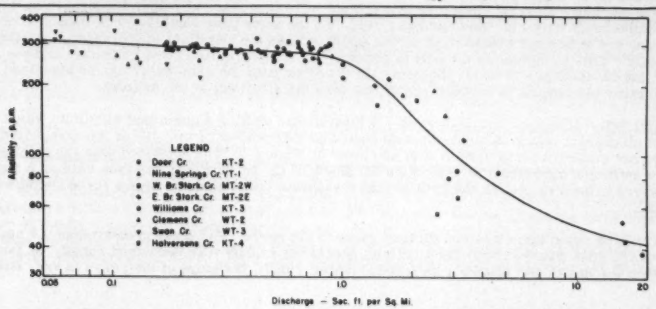

Fig. 2--Alkalinity rating-curve for tributaries to Madison Lakes

Measurement of alkalinity--The apparatus required is inexpensive, consisting of one 25- or 50-ml burette, preferably of the automatic type, one 50-ml volumetric pipette, one 200-ml porcelain casserole or evaporating dish, and one stirring rod. Two reagents are required, the first being fiftieth normal (0.02N) sulfuric acid which may be made up as follows: Purchase 1.00 normal sulfuric acid and prepare 0.02N by diluting 20.0 ml of 1.00 acid with distilled water to one liter of mixture. If a chemical laboratory is available each batch may be checked for standardization when made up. The second reagent is methyl-orange-indicator solution (0.05 per cent aqueous) made by dissolving one-half gram of powder in one liter of distilled water.

Pipette a 50-ml portion of the water-sample into a casserole, add one drop of methyl-orange-indicator solution and titrate with 0.02N acid until the original yellow color is changed to a pinkish bronze at a pH of 4.1 to 4.0. The titration in ml × 20 = ppm alkalinity.

Flood-runoff--During flood-periods alkalinity-samples were taken twice a day. The corresponding discharge was read from the alkalinity rating-curve and the results plotted to determine the flood-discharge hydrograph. These are plotted for three areas on Figure 3 and compared with the measured discharges. In general the agreement is satisfactory and the hydrographs are reasonable.

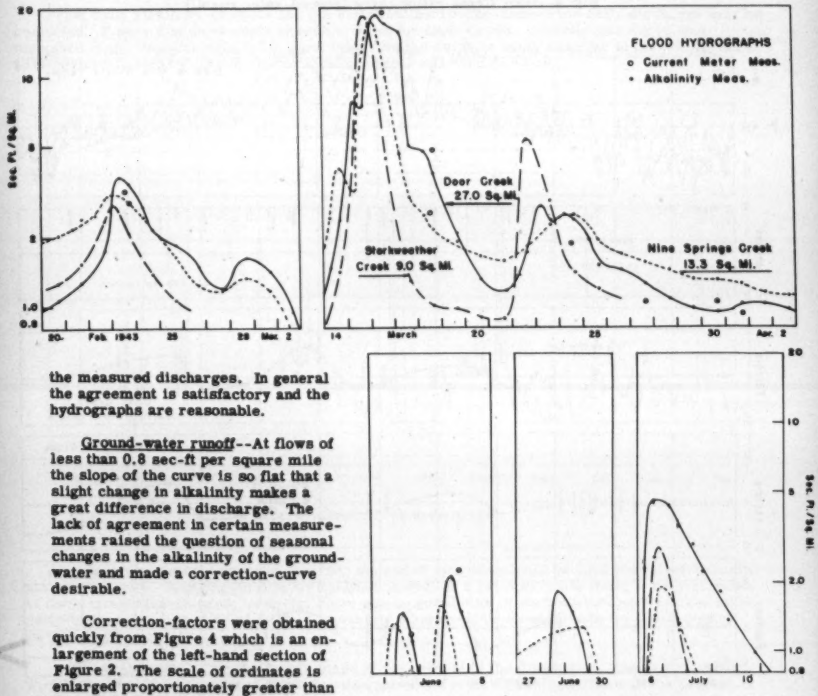

Fig. 3--Flood-hydrographs

Ground-water runoff--At flows of less than 0.8 sec-ft per square mile the slope of the curve is so flat that a slight change in alkalinity makes a great difference in discharge. The lack of agreement in certain measurements raised the question of seasonal changes in the alkalinity of the ground-water and made a correction-curve desirable.

Correction-factors were obtained quickly from Figure 4 which is an enlargement of the left-hand section of Figure 2. The scale of ordinates is enlarged proportionately greater than that of abscissas but both are still logarithmic. The points indicate the variation from the "standard curve"

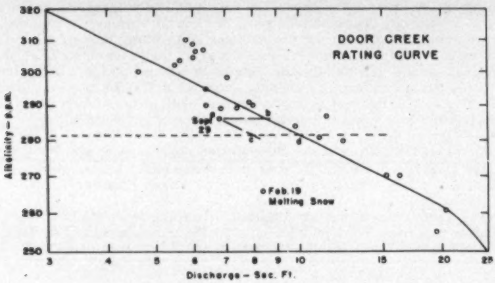

Fig. 4--Door Creek rating-curve (ground-water runoff)

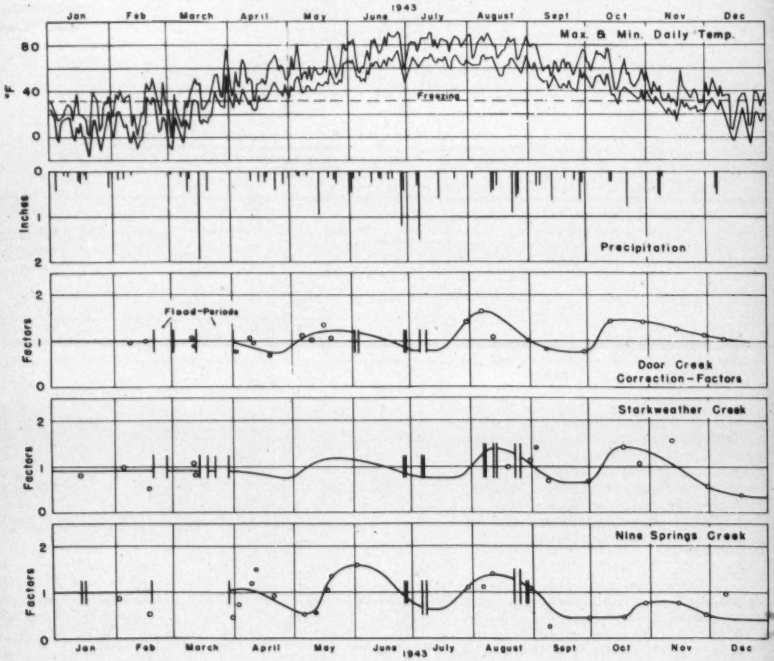

Fig. 5--Correction-factors

which has a correction-factor of 1.00. On September 29, for example, at alkalinity 286 the measured flow was 6.8 sec-ft, that from the curve 8.5; the correction-factor is the ratio of the two or 0.80. The same factor can be obtained more readily by following the dotted line a-c parallel to the standard to alkalinity 281, which is the standard value for ten sec-ft. The corresponding discharge-reading eight divided by ten also gives the factor 0.80.

When these factors are plotted chronologically as in Figure 5 for Door Creek, Nine Springs Creek, and Starkweather Creek, there is a surprising similarity.

Apparently dry periods make the correction-factor rise, because in 27 days, July 16 to August 11, with only two rains totalling 0.32 inch the factors increased. They did likewise again in 22 days from September 29 to October 20 with two rains totalling 0.40 inch. Conversely in 48 days with 13 rains totalling 5.56 inches from August 12 to September 28 the factors decreased. Such behavior is not unreasonable when one considers that during a rainy spell the higher ground-water level is due to recent accumulations of surface-water of lower alkalinity. Using this reasoning it is possible that the correction-factors for late June and early July are somewhat low. More data will shed considerable light on the variation to be expected.

From daily alkalinity-samples and the estimated correction-factors the daily discharge may be computed. Figure 6 is an example of such a curve for Door Creek. Actually this curve was smoothed in the final analysis but in most instances the curve is much superior to that which might have been estimated by current-meter measurements and rainfall alone.

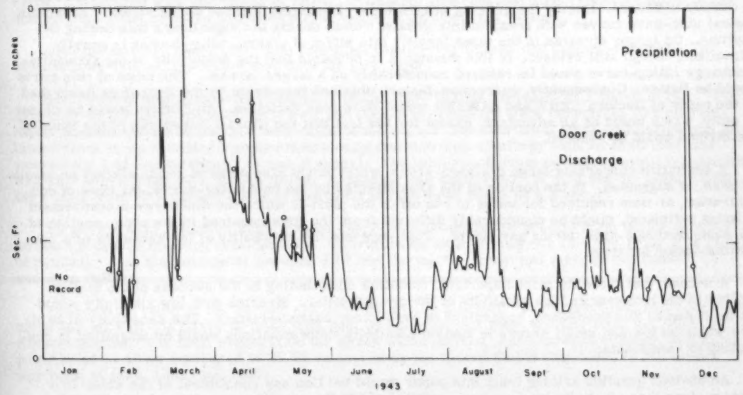

Fig. 6--Door Creek hydrograph

Conclusions--It is not intended that this method of analysis should be used where better methods are available. A gaging-station with a good control or a rated flume is much to be preferred. At these measuring-stations, however, there was no possibility of such construction and the alkalinity-method was indeed helpful. It is hoped that others will be stimulated to try it and report further on its limitations.

Acknowledgments--This study was made at the request of the Committee, Professor DANIEL W. MEAD, Chairman, appointed to conduct the survey. Dr. SAWYER is Director of the project, and Dr. LENZ is Hydrologic Consultant.

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DISCUSSION

ROBERT E. STIEMKE (University of North Carolina, Raleigh, North Carolina)--This paper by Doctors LENZ and SAWYER presenting a method of estimating stream-flow from alkalinity-determinations on samples of the water in a stream shows remarkable consistency in the data. The reasons for the undoubtedly good results are the fact that the streams and the water in them are particularly suited to this method and that the work was well done, and with due regard to the limitations of the procedure.

On various other occasions similar studies were made, but reversing the situation. Attempts were made to determine the quality or composition of water in a stream from stream-flow measurements. Because of the large number of factors influencing composition with varying runoff, none of these attempts was successful. The season of the year, the condition of cultivated land, and the intensity and length of a storm all affected the physical and many of the chemical properties of the water.

In this particular study in the Madison Lakes Region, the conditions necessary for success of the method are ideal. First, the drainage-areas of the streams are small--less than 25 square miles. This is necessary for consistent, reliable results because all parts of the area can be assumed to be under substantially identical precipitation-conditions for all storms. On a larger watershed, over which the intensity and amount of precipitation could vary considerably, this method of estimating stream-flow probably would show greater error. Speculating further on whether or not the method could be used on larger streams, several other observations can be made. Transpiration-losses show marked effect on the hourly variation of stream-flow in small streams in certain instances. During the growing season the hydrographs of these small streams resemble typical sine-wave curves with considerably greater runoff during the night hours than during the daytime. On larger streams in the same locality this effect of transpiration-losses is greatly minimized, though still evident. In like manner it is probable that the sensitivity of the alkalinity-discharge rating-curve would be reduced considerably on a larger stream. The slope of this curve would be flatter. Consequently, correction-factors obtained therefrom by the procedure described in the paper of Doctors LENZ and SAWYER would show less variation. All factors would be closer to unity, which would be an advantage, except for the fact that the overall sensitivity of the basis of the method would be reduced.

A limitation concerning large drainage-areas, which might also deserve consideration on smaller ones, is suggested. In the portion of the area affected by the backwater-curve, the time of concentration, or time required for water to run off to the point at which the discharge-measurement is being estimated, might be considerably different from the time required in the upper portion of the same drainage-area during any storm. This suggests the possibility of the necessity of a correction-factor for time.

A second, and probably most important, condition contributing to the success of the method applied is the necessarily high alkalinity of the ground-water. Streams with low alkalinity would not be suited to this procedure, regardless of their other characteristics. The sensitivity of basic data would be low and small errors in making alkalinity-determinations would be magnified in converting to runoff-data.

An obvious question arising from this paper would be: Can any constituent of the water in a stream other than alkalinity be used successfully? With the possible exception of salinity, it is doubtful that this would be possible. No other chemical property is found in sufficient quantity in most natural waters, and many that are present are relatively unstable, requiring analysis of samples without delay. Most of these analyses are more complicated and time-consuming or require more special equipment and reagents than the test for alkalinity. It is possible that the salinity, or salt-content, could be used with more or less success in determining the fresh-water flow of streams discharging through tidal estuaries, but an elaborate sampling procedure would be necessary because of the stratification of the fresh and salt water.

There is no doubt of the merit of this method of estimating stream-flow when the conditions are properly met, as they are in the case of the streams on which this work was carried out. E. D. BURCHARD, District Engineer, United States Geological Survey, Raleigh, North Carolina, was particularly impressed with results obtained. Along the southeastern seaboard there are many swamp-streams for which it is difficult to obtain a good discharge-measurement by conventional methods. He would be interested in trying the alkalinity-determination method, but it is impractical because of the low alkalinity of the water in these streams--as low as five to ten ppm. It is hoped

that others in localities wherein it could be tried are stimulated to obtain similar data on other streams.

The authors are to be complimented on the success of their studies and the significantly consistent data as well as the concise, understandable presentation of this paper.

CHECKING RUNOFF BY USE OF INFLOW- AND OUTFLOW-VOLUMES

Arno T. Lenz

It became necessary as part of the Madison Lakes Survey activities to determine the average discharge for monthly periods at or near the outlet of Lake Monona. Two possible locations were available for measuring-stations, one at Interlake Bridge [Station MO-5 (see Fig. 1 of preceding paper, p.)], the other at the inlet to Lake Waubesa (WT-1).

Attempts at direct measurement by current-meter were made at each location without success. At Interlake Bridge the river is about 200 feet wide and in the dredged navigation-channel four to six feet deep. At Waubesa Inlet the cross-section is obstructed by piles of a railroad bridge and is about 100 feet wide and eight to nine feet deep. Since the mean discharge for many months is 50 sec-ft the mean velocity often drops to less than 0.1 ft/sec. Barriers built out from the banks to the edge of the navigation-channel cut the width to 35 feet, but the mean velocity at low flow was still only 0.3 ft/sec. This was further complicated by the fact that a strong south wind raises the water at Waubesa Inlet and lowers the water at Monona Outlet. Reverse flow was actually measured with rod-floats at MO-5. It became apparent that direct measurements in the number that could be made economically would be of no practical value.

Average monthly flows were then computed considering inflow- and outflow-volumes. The method used will be illustrated with data for July, 1942.

River-inflow was measured at Mendota Outlet (MT-1R) and averaged 39.1 sec-ft in July. The stop-logs at the outlet-dam act as a weir and lake-level readings were correlated with current-meter measurements to obtain a weir-calibration curve. The flow from three tributaries was obtained from current-meter measurements supplemented with alkalinity data as described elsewhere [see 1 of "References" at end of paper]. The total runoff from measured small tributaries was 12.1 sec-ft from 29.1 square miles. Assuming this same runoff of 0.42 sec-ft/ square mile, the runoff from 12.5 square miles of unmeasured land-area would be 5.3 sec-ft.

To get the total inflow to Lake Monona there must be added the precipitation falling directly on the 5.5 square miles of lake-surface. This amounts to an average of 18.7 sec-ft for 3.79 inches of rainfall. Also the lake-level lowered 0.16 feet during the month and thereby contributed 9.2 sec-ft to outflow.

Evaporation reduced the outflow and contributes -30.2 sec-ft. The evaporation was computed using the MEYER-DALTON formula with data on humidity and wind-velocity from the Madison Airport Station. The total evaporation for seven warm months, April through October, was computed to be 31.16 as compared to 29.79 measured by the United States Engineers in Milwaukee way back in 1862, 1863, and 1865.

The algebraic sum of all increments totals 54.2 sec-ft and should give the mean discharge at MO-5.

Fortunately the United States Geological Survey has a gaging-station at Waubesa Outlet (WO-4). Therefore the contributions to and from Lake Waubesa may be added to the flow at Monona Outlet and the result should check the measured discharge within reason. These additions to the discharge for July were: Sewage-treatment plant, 19.7 sec-ft (from VENTURI-meter records); measured tributaries, 7.1 sec-ft; unmeasured tributaries, 6.1 sec-ft; precipitation on lake-surface, 9.5 sec-ft; storage 6.1 sec-ft; and evaporation, -20.1 sec-ft. These total 82.5 sec-ft and the measured discharge was 96.0 sec-ft. This agreement is not too bad but it does not consider the item of inflow from springs in the lake-bottom. It is well known that such do exist in all the Madison Lakes and since all months showed this lack of agreement it was arbitrarily assumed that the springs in the 9.2 square miles of lake-area contributed 11 sec-ft --six to Monona and five to Waubesa. These values were assumed from consideration of all months--not only July. Thus the computed flow for July is raised to 93.5 as compared to 96.0 measured. The remaining 2.5 sec-ft was distributed as

Table 1--Inflow- and outflow-volumes in second-feet per month

Item	Area	Month					
		Jan.	Feb.	March	April	May	June
	sq mi						
Mendota Outlet	254.0	96.4	139.0	207.0	210.0	75.6	84.2
Monona							
Measured tributaries	29.1	13.6	22.5	42.8	15.3	13.0	14.4
Unmeasured tributaries	12.5	1.7	3.6	24.9	13.6	14.0	22.8
Precipitation on Lake	5.5	10.1	2.3	14.3	9.6	10.8	20.4
		-10.1[a]	- 2.3[a]	+12.4[a]	....	...	...
Springs	....	1.0	1.0	6.0	6.0	6.0	6.0
Change in storage	....	0.6	- 15.3	- 53.0	+ 53.0	- 1.2	-15.5
Evaporation	....	- 1.8	- 4.3	- 7.3	- 18.6	-18.2	-27.0
Monona Outlet	301.1	111.5	146.5	247.1	288.9	100.0	105.3
Sewage-Treatment Plant	....	18.5	19.0	20.2	19.8	19.5	20.1
Waubesa							
Measured tributaries	24.3	13.3	20.7	43.2	12.0	9.0	11.7
Unmeasured tributaries	20.9	1.5	7.0	48.3	22.1	21.7	21.3
Precipitation on Lake	3.7	6.4	1.8	10.2	5.7	7.5	11.1
		- 6.4[a]	- 1.8[a]	+ 8.2[a]	....	...	...
Springs	....	1.0	1.0	5.0	5.0	5.0	5.0
Change in storage	....	0.4	- 1.3	- 30.4	+ 22.8	- 2.7	-15.7
Evaporation	....	- 1.2	- 2.9	- 4.8	- 12.3	-12.0	-17.8
Waubesa Outlet	350.0	145.0	190.0	347.0	364.0	148.0	141.0

Item	Area	Month					
		July	Aug.	Sep.	Oct.	Nov.	Dec.
	sq mi						
Mendota Outlet	254.0	39.1	37.2	39.4	33.4	73.8	64.9
Monona							
Measured tributaries	29.1	12.1	10.4	13.0	11.1	16.6	14.5
Unmeasured tributaries	12.5	7.1	3.5	6.0	5.9	2.9	8.2
Precipitation on Lake	5.5	18.7	9.3	28.6	5.9	14.0	8.9
Springs		6.0	6.0	6.0	6.0	3.0	3.0
Change in storage		9.2	13.8	- 8.3	13.2	3.0	5.2
Evaporation		-30.2	-25.6	-16.2	-15.4	- 7.0	- 1.6
Monona Outlet	301.1	62.0	54.6	68.5	60.1	106.3	103.1
Sewage-Treatment Plant		19.7	19.5	20.4	19.7	19.5	19.2
Waubesa							
Measured tributaries	24.3	7.1	5.2	8.9	8.4	12.2	12.0
Unmeasured tributaries	20.9	6.6	2.9	7.1	7.1	3.4	13.5
Precipitation on Lake	3.7	9.5	6.8	18.3	5.2	10.2	6.8
Springs		5.0	5.0	5.0	5.0	2.0	2.0
Change in storage		6.1	9.1	- 5.5	8.7	2.0	3.4
Evaporation		-20.0	-17.1	-10.7	-10.2	- 4.6	- 1.0
Waubesa Outlet	350.0	96.0	86.0	112.0	104.0	151.0	159.0

[a] Correction to balance.

a correction to the runoff from unmeasured areas, the final tabulation being made to check the measured flow perfectly.

In this way a balance was obtained for each month as shown in Table 1. The runoff from springs was reduced to three and two sec-ft for lakes Monona and Waubesa respectively for the months of November and December and to one sec-ft for each lake in January and February. This may be open to question but did help balance totals. As noted under "Precipitation on Lake" for January and February there is a correction to balance. Originally it was considered this precipitation in the form of snow was not effective until March. However the added weight of snow on the ice should be reflected in increased lake-level, and the unbalance should be carried simply as a correction.

In conclusion it should be noted that the numerical corrections applied to runoff from unmeasured areas to obtain the corrected discharge at Monona Outlet averaged five sec-ft or four per cent at the flow at that point. Six corrections were plus and six minus. The method was

indeed helpful in estimating the flow at Monona Outlet.

Acknowledgments--This study was made at the request of the Committee, Professor DANIEL W. MEAD, Chairman, appointed to conduct the survey. Dr. C. N. SAWYER is Director of the project and the writer is Hydrologic Consultant.

References

[1] A. T. LENZ and C. N. SAWYER, Estimation of stream-flow from alkalinity-determinations, Trans. Amer. Geophys. Union, Part VI, pp. 1005-1009, 1944.

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DISCUSSION

W. B. LANGBEIN (U. S. Geological Survey, Washington 25, D. C.)--The author is to be commended for his expert treatment of a problem not uncommon in many hydraulic or water-supply investigations, mainly that of transferring a record to another place on the same stream-course. The problem described by the author seems somewhat simpler than many in that there are two places of known discharge, one above and one below, and it is desired to determine the discharge at an intermediate location.

In all such transfers there are ever-present imponderables, such as evaporation and unmeasured local inflow, both surface and sub-surface. Adjustments for storage, though subject to error unless based on more than one gage, may be accepted as reliable. The accuracy of the estimates depends on how much the estimated quantities total in relation to the unknown discharge.

When assumptions are needed, it may be found most practical to make the assumption in such terms as to bring one closest to the answer. A simple assumption and one frequently made, is that discharge (losses, etc.) varies as the drainage-area. Since the point of unknown discharge is almost half-way intermediate between the two points of known discharge, it can be approximated by simple average of the discharges at the upstream and downstream points (measured sewage-effluent must be deducted from the discharge at Waubesa Outlet). The results so obtained are listed in Table 1 under "A".

Table 1--Estimate of monthly discharges

Month	Estimate A	Estimate B	Author's estimate
1942-43			
July	58	61.7	62.0
Aug.	51	56.8	54.6
Sep.	65	66.2	68.5
Oct.	59	62.4	60.1
Nov.	103	105.3	106.3
Dec.	102	104.5	103.1
Jan.	111	111.7	111.5
Feb.	155	148.8	146.5
Mar.	267	255.5	247.1
Apr.	277	293.8	288.9
May	102	104.8	100.0
June	102	104.0	105.3

If, however, the flows at Mendota Outlet and at Waubesa Outlet are adjusted for measured inflow and changes in storage and these results averaged, discharges as listed in Table 1 under "B" are obtained. Such estimates compare favorably with those of the author and of course the true or actual discharges are unknown in both instances.

The title used by the author might equally well be extended to verification of runoff-records in a drainage-basin by study of runoff for intervening areas in humid and subhumid-climates. Thus monthly runoff-volumes at an upper station, together with measured runoff from local tributaries, are subtracted from the volumes during corresponding months measured at the lower stations and the difference expressed in inches over the unmeasured intervening area. The unit-runoff thus determined by differences between two larger quantities magnifies all errors contained in the two large quantities. The unit-runoff is studied in relation to the runoff measured in adjacent or nearby areas. Wide discrepancies signal that one or the other station-record contains an error. Repetition of the method for other intervening and measured areas generally isolates the error.

For many detailed examinations of day-by-day runoff, a difference in runoff-volume between stations must be accounted for in a systematic way in relation to storage (gage-height) within an intervening reach or partial basin-area.

FLOOD-STORAGE ACCOUNTING

C. O. Clark

Runoff on the watershed of a large river may be determined from stream-flow during flood-producing rainfall by application of storage-accounting methods. Within the time-limits imposed by communications, a well-gaged river-system may be utilized contemporaneously as a single runoff-gage. A technique for volumetric calibration of the river-channels and valleys and interpreting the valley-storage changes as indices of total runoff is illustrated for the Potomac River above Washington, D. C.

Just as a series of ground-elevation observations at an airport construction project can be used to indicate the volume of earth to be moved and the rate at which it is being moved, so can a series of water-surface elevations along a river-channel be used to indicate the volume of water stored therein and the rate at which it is being passed. In both cases the accuracy of the conclusions are dependent upon the number of locations at which observations are made and the frequency of observation, but quite usable values may be obtained with many less observations than might be required for highly accurate values.

This paper attempts to demonstrate:

(1) That gages in use to determine rates at which water is passing in major watercourses, may also be used as the observation-points to determine the volume of water in these major watercourses.
(2) That determinations of storage volume in relationship to stage and/or discharge are established routines.
(3) That the appropriate use of these routines permits the detection of large proportions of the total runoff-volume in the major watercourses of the river-system.
(4) That, where the storage-accounting in major watercourses includes all long tributaries, and thus leaves the remaining minor watercourses as only a large number of relatively short streams, the storage in these minor watercourses can be estimated from the changes in the runoff-volume in major watercourses.
(5) That, communications permitting, the stage-observations at and prior to any selected time during flood-rainfall are sufficient to provide an accurate estimate of flood-runoff available at the selected time.

Flood-storage accounting is simply a reverse application of standard flood-routing procedure. The same tools, the unit-hydrograph and flood-routing techniques, which permit the office calculation of a flood-hydrograph from runoff on the ground can be reversed and used to calculate the runoff on the ground from known hydrographs.

The principle of flood-storage accounting, like flood-routing, is based upon application of the fundamental storage-equation (1).

$$\text{Outflow (O)} = \text{Inflow (I) minus rate of change of storage } (ds/dt) \quad \ldots\ldots\ldots\ldots (1)$$

In flood-routing, items (I) and (ds/dt) are known and solution is for item (O). In flood-storage accounting, items (O) and (ds/dt) are known and solution is for item (I). Both processes provide for solutions at any given instant from data known at the same time; neither is a forecast.

Any relationship between valley-storage and discharge which is adequate for flood-routing purposes may be used in flood-storage accounting. Because of its simplicity in tabular computation and its suitability to the Potomac River System, the relationships of the Muskingum Method of flood-routing are illustrated in this paper. In this method, valley-storage volume in any reach of river is directly proportional to the flow in that reach as in equation (2)

$$S = KQ \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

and the flow in the reach is determined as a weighted value of the inflow and outflow thereof, or

$$Q = xi + (1-x)\,o \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

where: S = storage, in (cubic feet per second)-hours or acre-feet; K = a constant, dimensionally hours or acre-feet per cfs; Q = flow in the river reach, in cubic feet per second; x = a constant,

Table 1--Valley-storage capacity of natural watercourses, Potomac River Basin

Gage		Source to gage[a]			To next downstream gage			
Stream	Station	Drainage area	Storage		cfs-hrs	ac-ft	ac-ft	Relative influence-upstream gage
			TC[b]	k[c]	cfs	cfs	cfs-mi	
		sq mi	hr	hr				
North Branch Potomac	Bloomington	287	10	10	6	0.50	.024	0.4
North Branch Potomac	Pinto	122	9	6	4	0.33	.025	0.5
North Branch Potomac	Cumberland	32	4	4	14	1.17	.042	0.5
Potomac River	Paw Paw	547	18	8	9	0.75	.020	0.4
Potomac River	Hancock	294	9	6	14	1.17	.021	0.5
Potomac River	Shepherdstown	1369	30	6	7	0.58	.024	0.5
Potomac River	Point of Rocks	394	10	10	9	0.75	.016	0.5
Potomac River	Washington	653	18	15	..	...	...	..
Savage River	Bloomington	115	11	5	6	0.50	.024	0.4
Georges Creek	Franklin	72	5	5	6	0.50	.025	0.4
Wills Creek	Cumberland	247	8	4	2	0.17	.042	0.5
Patterson Creek	Headsville	216	12	6	14	1.17	.038	0.5
South Branch Potomac	Petersburg	642	15	12	8	0.67	.011	0.5
South Branch Potomac	Springfield	546	24	12	10	0.83	.038	0.5
South Branch South Fork	Moorefield	283	13	9	8	0.67	.013	0.5
Cacapon River	Yellow Springs	306	10	6	15	1.25	.017	0.57
Cacapon River	Great Cacapon	364	16	8	4	0.33	.021	0.4
Conococheague Creek	Fairview	494	30	12	12	1.00	.022	0.5
Antietam Creek	Sharpsburg	281	24	10	7	0.58	.023	0.5
North River	Burketown	375	9	4	5	0.42	.023	0.3
South Fork Shenandoah	Lynnwood	197	6	3	9	0.75	.017	0.5
South Fork Shenandoah	Luray	301	9	4	12	1.00	.020	0.5
South Fork Shenandoah	Front Royal	261	15	6	14	1.17	.022	0.4
Shenandoah River	Millville	442	16	8	7	0.58	.034	0.5
Middle River	Grottoes	360	12	6	3	0.25	.025	0.3
South River	Waynesboro	144	12	6	9	0.75	.026	0.3
North Fork Shenandoah	Strasburg	772	20	7	16	1.33	.022	0.4
Passage Creek	Buckton	87	6	3	18	1.50	.026	0.4
Cedar Creek	Winchester	101	6	2	19	1.58	.023	0.4
Monocacy River	Jug Bridge	817	28	14	12	1.00	.017	0.5
Goose Creek	Leesburg	338	17	8	6	0.50	.012	0.5
Seneca Creek	Dawsonville	101	6	3	4	0.33	.012	0.5

[a] Below other upstream gages only. [b] TC=Time of concentration, translatory storage-factor. [c] k=Reductive storage-factor.

of non-dimensional value less than 1.0, indicating relative influence of flow at upstream gage; i = inflow to the reach, in cubic feet per second; and o = outflow from the reach, in cubic feet per second.

The relationships between valley-storage and discharge in the major watercourses of the Potomac River, within the limits of collection of stream-flow records, were developed by conventional flood-routing procedure applied to the short reaches between existing stream-gages. These relationships were found to be as shown in Table 1.

In the application of these storage-relationships to valley-storage accounting, as in flood-routing, the discharge at each gage within the river-system is taken as indicative of storage between gages in accordance with formulas (2) and (3).

The application to a single reach is illustrated, using that Potomac River Reach immediately above Washington, from Point of Rocks, Maryland, to Washington. Table 1 indicates that valley-storage in this reach averages nine cfs-hours (or 0.75 acre-foot) per cfs of flow and that flow in the reach may be taken as 0.5 of the inflow plus 0.5 of the outflow. This relationship applies to the flow which travels the entire length of the reach, and intermediate flows can be treated separately and proportionally. Since only 9,651 square miles of watershed contribute to flow from

above Point of Rocks and 11,560 square miles contribute to Washington, it is assumed that (9,651/11,560) is the proportion of Washington flow (W) which results from flow measured at Point of Rocks (PR). Thus

$$S = KQ = K\,[xi + (1-x)o] \quad \ldots\ldots (4)$$

$$= 0.75\,[0.5\ PR + 0.5\ (9{,}651/11{,}560)\,W] \quad \ldots\ldots (5)$$

$$= 0.38\ PR + 0.32\ W \quad \text{in acre-feet} \quad \ldots\ldots (5a)$$

Similar applications for the elements of the inflow to this reach below Point of Rocks, add 0.06 to the constant for the Washington discharge, to make a total storage in that reach of 0.38 acre-feet per cfs, indicated by the flow at Washington. Storage in the reach above Point of Rocks, also indicated by discharge at that gage, amounts to 0.28 acre-foot per cfs, giving a total of 0.66 acre-feet per cfs (0.38 + 0.28 = 0.66), indicated by the flow at Point of Rocks. The values similarly expressed for discharges at other gaging-stations are shown in Table 2. Where local inflows are ungaged, they are assumed, for estimating storage only, to be directly proportional to flows at a nearby gaging-station on a small watershed, and so indicated in Table 2.

Defining the flood-channel of the streams within the limits of the above-listed stream-gages as the major watercourses, it is possible to determine during flood-time the storage on each side of the gage for which discharge (or stage) is known. These data can be collected by radio or telegraph at any time at which the cost of collection is justified by the beneficial use of the results. The data are available for the two most severe Potomac River floods of the last decade, and it may be assumed that appropriate communications could have made them available to an operating organization in a relatively short time, so that they could have been utilized immediately during the flood.

Application of valley-storage accounting in a typical flood--The mechanical process of accounting for storage in the major watercourses during a typical flood of the Shenandoah River above Millville, one of two major tributaries of the Potomac River, is illustrated on Figure 1. On this Figure is shown a record of discharge which might have resulted from rainfall in the first 18 hours of the first day. Following the records, is the compilation of storage in the major watercourses.

Inflow to the major watercourses is then determined as the rate of change of storage plus the outflow-rate at Millville [equation (1)]. Hydrographs of flow-rate, mass-curves of flow-volume, and storage are shown on Figure 1. In the mass-curve, only the ordinate of total storage in major watercourses is shown, but this total is of 11 separate components tabulated above the curve.

Storage in the minor watercourses, beyond the gaged limits of the major watercourses, may be estimated by determining the approximately constant relationship between storage in the minor watercourse and the flow from that storage, namely the inflow to the major watercourses. Studies indicated that this relationship for the Shenandoah River was 1.5 acre-feet per cfs of inflow to major watercourses. Adding this amount to the volume of inflow to the major watercourse, determines the mass-curve of inflow to minor watercourses, as shown on Figure 1, which is a close approximation of the runoff which produced the flood.

Lest there be any uncertainty regarding Figure 1, the typical flood is merely an 18-hour unit-hydrograph of 3.0-inch volume, each of the station "records" are likewise three-inch unit-graphs. This is the only kind of a flood for which the runoff which produced the flood can be known; in any actual flood it is only possible to compare the runoff which produced the flood as computed by this method with that computed by some other method. No actual measurement of runoff on the ground is yet possible.

The Shenandoah River from above Millville, 3,040 square miles, combines with the Potomac River from above Shepherdstown, 5,936 square miles, and flows to Washington through a large storage-reach in which it may be joined by additional flow-volume from 2,584 square miles of contributing area. Storage-accounting for the Potomac River above Shepherdstown, Figure 2, is accomplished in the same manner as illustrated for Shenandoah River above Millville. For the 2,584 square miles of watershed below the junction of these major components, valley-storage in the major watercourses is accounted in the same manner. However, the total inflow to this channel-storage includes the flow of the upstream areas gaged at Millville and Shepherdstown, and these elements must be subtracted from total inflow to the major watercourse to get the local

Table 2--Valley-storage in the major watercourses of the Potomac River

Stream	Gaging-station	Drainage-area	Valley-storage	
			Per cfs	For one cfs/sq mi
		sq mi	ac-ft	ac-ft
Savage River	Bloomington	115	0.20	23
North Branch Potomac	Bloomington	287	0.20	57
Georges Creek	Franklin	72	0.37[a]	27
North Branch Potomac	Pinto	596	0.47	280
Wills Creek	Cumberland	247	0.09	22
North Branch Potomac	Cumberland	875	0.75	656
Patterson Creek	Headsville	216	1.75[a]	378
South Branch Potomac	Petersburg	642	0.33	212
South Fork South Branch	Moorefield	283	0.33	93
South Branch Potomac	Springfield	1,471	0.75	1,103
Potomac River	Paw Paw	3,109	0.80	2,487
Cacapon River	Yellow Spring	306	1.20[a]	367
Cacapon River	Great Cacapon	677	0.76	515
Potomac River	Hancock	4,073	0.97	3,951
Conococheague Creek	Fairview	494	0.50	247
Patterson Creek	Headsville	216	1.88[a]	406
Potomac River	Shepherdstown	5,936	0.51	3,027
Total above Shepherdstown		5,936	2.33	13,851
North River	Burketown	375	0.10	38
South Fork Shenandoah	Lynnwood	1,076	0.67	721
South Fork Shenandoah	Luray	1,377	0.88	1,212
South Fork Shenandoah	Front Royal	1,638	0.97	1,589
Shenandoah River	Millville	3,040	0.75	2,280
Middle River	Grottoes	360	0.08	29
South River	Waynesboro	144	0.22	32
North Fork Shenandoah	Cootes Store	215	0.33	71
North Fork Shenandoah	Strasburg	772	1.03	795
Cedar Creek	Winchester	101	0.63	64
Passage Creek	Buckton	87	5.33[a]	464
Total above Millville		3,040	2.40	7,295
Potomac River	Shepherdstown	5,936	0.29	1,721
Shenandoah River	Millville	3,040	0.29	882
Monocacy River	Jug Bridge	817	0.50	408
Antietem Creek	Sharpsburg	281	0.29	81
Passage Creek	Buckton	87	0.66[a]	57
Potomac River	Point of Rocks	9,651	0.66	6,370
Goose Creek	Leesburg	338	0.90[a]	304
Potomac River	Washington	11,560	0.38	4,393
Total above Washington but below Shepherdstown and Millville		11,560	1.23	14,216
Total above Washington		11,560	3.06	35,362

[a] Flow at this station used as index of flow from other ungaged areas in vicinity on a drainage-area proportion.

inflow to major watercourses which is tabulated in Figure 3 for the local area. The lower tabular portion of Figure 3 adds the flow-elements for the local area to the similar elements computed in Figures 1 and 2 for the component areas above Millville and Shepherdstown.

The Figures presenting storage-accounting procedure have been illustrated for computed unit-graph floods; so far, no actual flood-data have been used (except in the derivation of the original unit-hydrographs). In these typical floods, the mass-curve of inflow to minor watercourses has been made to approximate the mass-curve of runoff during the period of runoff-producing rainfall.

	Days	1					2				3				4				5				6			
	Hour	0	6	12	18	24	6	12	18	24	6	12	18	24	6	12	18	24	6	12	18	24	6	12	18	24
Record of Discharge 1,000 c.f.s.	Burkstown	0	9	24	28	20	6	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Lynnwood	0	10	36	61	64	44	20	8	4	3	3	2	2	2	2	2	2	2	2	2	2	2	2	2	2
	Luray	0	2	20	47	73	71	49	23	8	4	3	3	3	3	3	3	2	3	3	3	2	3	3	3	3
	Front Royal	0	0	2	18	42	70	78	70	49	30	17	10	7	5	4	4	4	4	3	3	3	3	3	3	3
	Millville	0	-1	9	24	55	80	102	108	101	83	61	42	28	19	14	10	9	8	7	7	6	6	6	6	6
	Grottoes	0	2	14	23	24	14	6	3	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Waynesboro	0	1	6	9	9	5	2	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Cootes Store	0	14	15	15	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Strasburg	0	2	11	31	46	45	28	13	7	4	3	2	2	2	2	2	2	2	2	1	1	1	1	1	1
	Winchester	0	6	8	8	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Buckton	0	4	6	7	3	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Storage, Major Watercourses 1,000 acre-feet	Discharge x Factor																									
	Burkstown .10	0	1	2	3	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Lynnwood .67	0	7	24	41	43	30	14	6	2	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Luray .88	0	0	18	41	64	62	43	21	7	3	3	3	3	3	2	2	2	2	2	2	2	2	2	2	2
	Front Royal .97	0	0	2	18	40	68	76	68	48	29	17	10	7	5	4	4	4	3	3	3	3	3	3	3	3
	Millville .75	0	-1	7	18	41	60	77	81	76	63	46	32	21	14	10	8	6	6	5	5	5	5	5	5	5
	Grottoes .08	0	0	1	2	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Waynesboro .22	0	0	1	2	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Cootes Store .33	0	5	5	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Strasburg 1.03	0	2	11	32	47	46	29	13	7	4	3	2	2	2	2	2	2	2	2	1	1	1	1	1	1
	Winchester .63	0	4	5	5	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Buckton 5.33(a)	0	19	33	35	17	3	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Total Storage in Major Watercourses (c)	0	37	109	202	260	272	241	190	141	102	71	49	35	26	20	18	16	15	14	13	13	13	13	12	12
Total Flood-Flow	Rate of Change of Storage (b)	0	109	165	151	70	-19	-82	-100	-88	-70	-53	-36	-23	-15	-8	-4	-3	-2	-2	-1	0	0	-1	-1	
	Inflow to Major Watercourses (b)	0	108	174	175	125	61	20	8	13	13	8	6	5	4	6	6	6	6	5	6	6	6	5	5	
	Storage in Minor Watercourses (c) (d)	0	162	261	262	186	92	30	12	20	20	12	9	8	6	9	9	9	9	8	9	9	9	8	8	
	Storage, Major and Minor Watercourses (c)	0	199	370	464	446	364	271	202	161	122	83	58	43	32	29	27	25	24	22	22	22	22	21	20	
	Rate of Change of Storage (b)	398	370	265	78	-100	-177	-162	-110	-80	-78	-64	-40	-26	-14	-5	-4	-3	-3	-2	0	0	-1	-2		
	Inflow to Minor Watercourses (b)	398	369	274	102	-45	-97	-60	-2	21	5	-3	2	2	5	9	6	6	5	5	7	6	5	4		
	Σ Flow at Millville (c)	0	0	1	10	30	64	109	162	214	260	296	321	339	351	359	365	369	373	377	380	384	387	390	393	396
	Σ Inflow to Major Watercourses (c)	0	37	110	212	290	336	350	352	355	362	367	370	374	377	379	383	385	388	391	393	397	400	403	405	408
	Σ Inflow to Minor Watercourses (c)	0	199	371	474	478	428	380	364	375	382	379	379	382	383	388	392	394	397	399	402	406	409	411	413	

(a) Index gage for nearby ungaged areas. (b) 1,000 c.f.s. (c) 1,000 acre-feet. (d) Storage in Minor Watercourses = 1.5 x Inflow to Major Watercourses.

Table A--Data for Figure 1 (all values rounded from original data and computations)

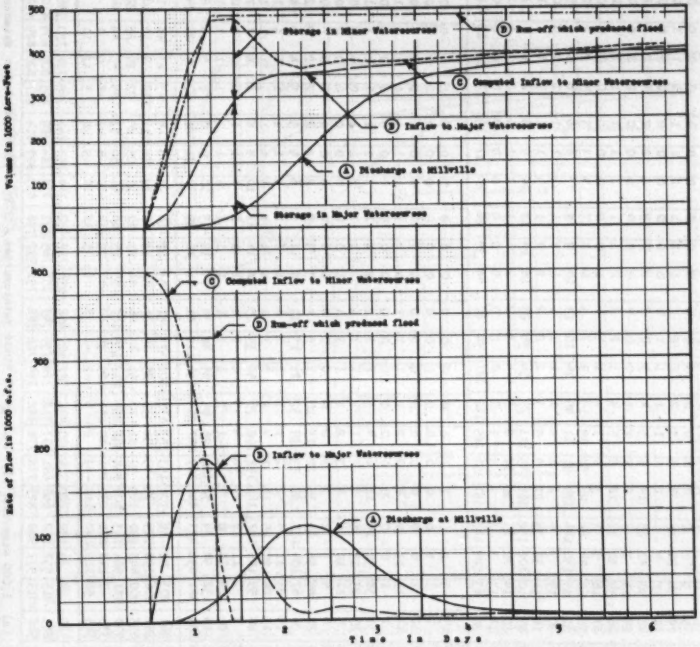
Storage in Minor Watercourses
(D) Run-off which produced flood
(C) Computed Inflow to Minor Watercourses
(B) Inflow to Major Watercourses
(A) Discharge at Millville
Storage in Major Watercourses
Volume in 1000 Acre-Feet
Rate of Flow in 1000 c.f.s.
Time in Days

Fig. 1--Storage accounting for typical flood, Shenandoah River above Millville

Applied to larger or smaller floods of the same duration of uniform runoff, the process works equally well. For shorter duration of runoff, the amount would be slightly overestimated, while in longer durations of runoff, it would be underestimated. Because inflow to minor watercourses is the algebraic sum of runoff as inflow to the watershed and infiltration to ground-storage which is a negative inflow, inflow to minor watercourses will deviate from the mass-curve of runoff on the watershed by the amount of storage in ground-water. Such deviation is shown in Figures 1, 2, and 3. Obviously, however, this infiltration occurs during the 18-hour runoff-period, too, and has been deliberately obscured, by overestimation of the constant expressing storage in the minor watercourses, in order that the mass-curves of inflow to minor watercourses and of runoff might agree for a typical flood-duration.

The preliminary analysis necessary to establishment of storage-accounting in a river-basin has been set forth. The steps in that analysis have included:

(a) Determination of channel storage relations by flood-routing analysis;
(b) determination of unit-hydrographs at all stations;
(c) application of storage-accounting to the channel, or major watercourses, with the unit-hydrograph floods typical of the river, to determine inflow to the major watercourses; and
(d) determination of the relationship between storage in the minor watercourses and outflow therefrom (inflow to major water-courses) in the typical flood.

		Days	1					2				3				4				5				6			
		Hour	0	6	12	18	24	6	12	18	24	6	12	18	24	6	12	18	24	6	12	18	24	6	12	18	24
Record of Discharge 1,000 c.f.s.	Bloomington (N.B.)		0	2	10	16	17	11	6	4	2	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Bloomington (S)		0	2	6	8	7	3	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Franklin		0	2	5	5	3	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Pinto		0	2	15	29	36	28	16	9	5	3	2	2	2	1	1	1	1	1	1	1	1	1	1	1	1
	Cumberland (W.C.)		0	7	16	18	12	4	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0
	Cumberland		0	4	22	41	50	40	25	14	8	5	4	3	2	2	2	2	2	2	2	2	2	2	2	2	2
	Headsville		0	3	9	14	13	7	3	2	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0
	Petersburg		0	2	12	26	34	30	19	12	8	5	4	3	2	2	2	1	1	1	1	1	1	1	1	1	1
	Moorefield		0	4	12	17	16	9	5	3	2	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0
	Springfield		0	-1	6	30	60	74	66	46	30	19	13	9	7	5	4	4	3	3	3	3	2	2	2	2	2
	Paw Paw		0	-2	4	32	83	130	144	124	91	61	40	26	18	13	10	9	8	7	6	6	5	5	5	5	5
	Yellow Spring		0	4	14	20	19	9	4	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Great Cacapon		0	1	7	18	31	38	33	21	9	5	3	2	2	2	2	2	1	1	1	1	1	1	1	1	1
	Hancock		0	4	14	29	60	108	152	166	145	111	79	54	36	25	18	14	12	10	9	9	8	8	7	7	7
	Fairview		0	0	4	10	14	22	21	18	12	8	5	4	3	2	2	1	1	1	1	1	1	1	1	1	1
	Headsville		0	3	9	14	13	7	3	2	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Shepherdstown		0	-1	7	30	63	106	145	181	196	189	162	127	94	67	48	34	26	20	17	15	13	12	12	11	10
Storage in Major Watercourses 1,000 acre-feet	Discharge x factor																										
	Bloomington (N.B.)	0.20	0	0	2	3	3	2	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Bloomington (S)	0.20	0	0	1	2	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Franklin	.37	0	0	2	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Pinto	.47	0	1	7	14	17	13	8	4	2	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Cumberland (W.C.)	0.09	0	1	1	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Cumberland	.75	0	3	16	31	38	30	19	11	6	4	3	2	2	2	2	1	1	1	1	1	1	1	1	1	1
	Headsville	1.75 (a)	0	5	16	25	23	13	5	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Petersburg	.33	0	1	4	9	11	10	6	4	3	2	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0
	Moorefield	.33	0	1	4	6	5	3	2	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Springfield	.75	0	-1	5	22	45	56	49	35	22	15	10	7	5	4	3	3	2	2	2	2	2	2	2	2	2
	Paw Paw	.80	0	-1	3	26	67	104	115	99	73	49	32	21	15	11	8	7	6	6	5	5	5	4	4	4	4
	Yellow Spring	1.20 (a)	0	4	17	24	23	11	5	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Great Cacapon	.76	0	1	5	13	24	29	25	16	7	4	2	2	1	1	1	1	1	1	1	1	1	1	1	1	1
	Hancock	.97	0	4	14	28	59	105	147	161	141	108	76	52	35	25	18	14	11	10	9	8	8	8	7	7	7
	Fairview	.50	0	0	2	5	7	11	11	9	6	4	3	2	1	1	1	1	1	1	1	1	1	0	0	0	0
	Headsville	1.55 (a)	0	6	18	26	24	14	6	3	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Shepherdstown	.51	0	0	3	15	32	54	74	92	100	96	83	65	48	34	24	18	13	10	9	8	7	6	6	6	5
	Total Storage in Major Watercourses (c)		0	26	120	253	381	456	473	440	367	287	214	156	112	81	61	46	39	34	31	28	27	25	24	24	23
Total Flood Flow	Rate of Change of Storage (b)		0	120	227	261	203	92	-16	-106	-153	-153	-131	-102	-75	-51	-33	-22	-14	-8	-6	-4	-3	-3	-1	-1	
	Inflow to Major Watercourses (b)		0	119	234	291	266	198	129	75	43	36	31	25	19	16	15	12	12	12	11	11	10	9	11	10	
	Storage in Minor Watercourses (c) (d)		0	268	526	655	600	445	290	169	97	81	70	56	43	36	34	27	27	27	25	25	22	20	25	22	
	Storage, Major and Minor Watercourses (c)		0	294	646	908	981	901	763	609	464	368	284	212	155	117	95	75	66	61	56	53	49	45	49	46	
	Rate of Change of Storage (b)		588	646	614	335	-7	-218	-292	-299	-241	-180	-156	-129	-95	-60	-42	-29	-14	-10	-8	-7	-8	0	1		
	Inflow to Minor Watercourses (b)		588	645	621	365	56	-112	-147	-118	-45	9	6	-2	-1	7	6	5	12	10	9	8	5	12	11		
	Σ Flow at Shepherdstown (c)		0	0	1	10	34	76	139	220	314	410	498	572	627	668	696	717	732	744	753	761	768	775	780	786	791
	Σ Inflow to Major Watercourses (c)		0	26	121	263	415	532	612	660	681	697	712	728	739	749	757	765	771	778	784	789	795	800	804	810	814
	Σ Inflow to Minor Watercourses (c)		0	294	647	918	1015	977	902	829	778	778	782	784	782	785	791	792	798	805	809	814	817	820	829	832	

(a) Index gage for nearby ungaged areas. (b) 1,000 c.f.s. (c) 1,000 acre-feet. (d) Storage in Minor Watercourses = 2.25 x Inflow to Major Watercourses.

Table B--Data for Figure 2 (all values rounded from original data and computations)

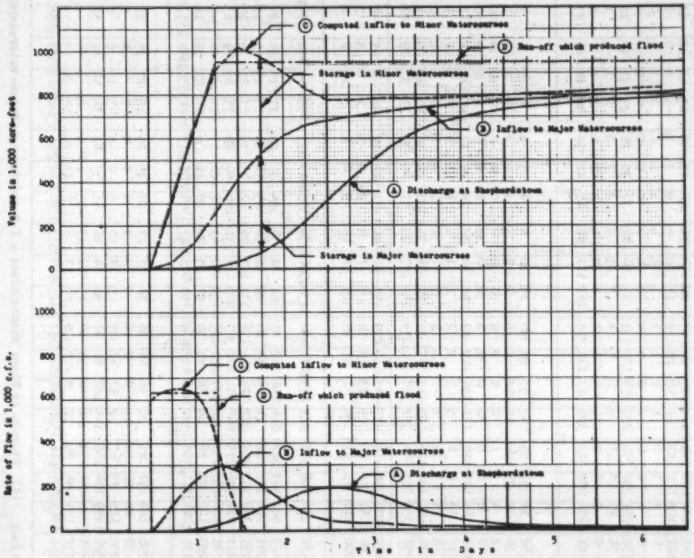
Volume in 1,000 acre-feet
Rate of Flow in 1,000 c.f.s.
Time in Days
(C) Computed Inflow to Minor Watercourses
(D) Run-off which produced flood
Storage in Minor Watercourses
(B) Inflow to Major Watercourses
(A) Discharge at Shepherdstown
Storage in Major Watercourses

Fig. 2--Storage accounting for typical flood, Potomac River above Shepherdstown

Thus, the entire outlined process is merely a solution of the query, "Using these unit-hydrographs, what runoff is required to produce the stream-flow and storage-changes which are being experienced?"

The storage-accounting procedure is demonstrated by application to the records of the flood of October 1942, the largest flood of record at many points in the Shenandoah River Basin, moderate on the Potomac River above Shepherdstown and near-record at Washington. Rainfall varied from two to 19 inches. Thus, the flood-runoff was not uniform in areal distribution. Runoff was generated from 12^h on October 13 to 24^h on October 15 with the greater portion on October 15. Thus, the flood-runoff was much longer than the assumed typical 18 hours, and not chronologically uniform. The process of computation is illustrated for the flood-records of 1942 on Figures 4, 5, and 6.

The validity of the accounting procedure can be demonstrated only by comparison with a runoff-determination by some other method. Such an alternative determination is shown on Figures 4, 5, and 6 as the "runoff which produced flood". This line was determined from the entire flood-record at each station, rainfall-records, and a laborious series of unit-hydrograph calculations in which the flood-record at each station was reproduced closely by the unit-hydrograph method, using the amount and distribution of runoff on each drainage-area component which was deemed most applicable, revised and retried until suitable conformity with records was obtained. The sum of such runoff-volumes was taken as the alternative determination of runoff which produced the flood, and compares well with the rising mass-curve of inflow to minor watercourses. The alternative determination is "more conventional"; the indeterminate elements in its derivation would hardly permit appropriate use of the term "more accurate".

		Days	1				2				3				4				5				6			
		Hour	0	6	12	18	24	6	12	18	24	6	12	18	24	6	12	18	24	6	12	18	24	6	12	18	24
Record of Discharge 1,000 c.f.s.		Shepherdstown	0	-1	7	30	63	106	145	181	196	189	162	127	94	67	48	34	26	20	17	15	13	12	12	11	11
		Millville	0	-1	9	28	59	80	102	108	101	83	61	42	28	19	14	10	9	8	7	7	6	6	6	6	6
		Sharpsburg	0	0	2	4	6	7	6	4	3	2	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0
		Duckton	0	4	6	7	3	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Point of Rocks	0	4	11	33	70	128	192	251	292	301	280	234	180	131	93	66	49	37	30	26	23	21	19	18	18
		Frederick	0	1	7	15	26	33	34	27	18	13	9	6	5	4	3	3	2	2	2	2	2	1	1	1	1
		Leesburg	0	1	9	17	20	16	9	5	3	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
		Washington	0	2	14	31	76	123	188	238	262	314	326	313	271	215	161	117	85	61	42	37	28	28	25	23	22
Storage in Watercourses	Major	Discharge x factor																									
		Shepherdstown 0.29	0	0	2	9	19	31	42	53	57	55	47	37	28	20	14	10	8	6	5	4	4	3	3	3	3
		Millville 0.29	0	0	3	7	16	24	30	32	29	24	18	12	8	5	4	3	3	2	2	2	2	2	2	2	2
		Sharpsburg 0.29	0	0	0	1	2	2	2	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Duckton 0.66 (a)	0	2	4	4	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Point of Rocks 0.66	0	2	7	22	46	85	127	165	192	199	188	154	119	87	62	44	32	24	20	17	15	14	13	12	12
		Frederick 0.50	0	1	3	7	13	17	17	13	9	6	5	3	2	2	1	1	1	1	1	1	1	1	1	1	1
		Leesburg 0.90 (a)	0	1	8	15	18	14	9	5	3	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0
		Washington 0.38	0	1	5	12	29	46	70	89	109	118	123	117	103	81	60	44	31	23	16	14	10	10	9	8	8
		Total Storage in Major Watercourses (a)	0	7	32	77	145	219	297	358	397	404	382	326	261	196	142	103	76	57	45	39	33	31	29	27	26
	Minor	Rate of Change of Storage (b)	0	32	70	113	142	152	139	100	46	-15	-78	-121	-130	-119	-93	-66	-46	-31	-18	-12	-8	-4	-4	-3	
		Inflow to Major Watercourses (b)	0	36	68	90	100	89	80	47	31	27	25	23	19	10	6	7	4	2	0	3	1	1	3	3	
		Storage in Minor Watercourses (c) (d)	0	90	170	225	250	223	200	118	77	67	62	57	47	25	15	18	10	5	0	8	3	15	8	8	
Flood Flow in Watercourses	Major	Σ Flow at Washington (c)	0	1	5	16	43	92	170	278	406	555	715	875	1021	1142	1236	1306	1356	1393	1419	1439	1455	1469	1482	1494	1505
		Storage in Major Watercourses																									
		Above Shepherdstown (c)	0	26	120	253	381	456	473	440	367	287	214	156	118	81	61	48	39	34	31	28	27	25	24	24	23
		Above Millville (c)	0	37	109	202	260	272	241	190	141	102	71	49	35	26	20	18	16	15	14	13	13	13	13	12	12
		Below Shepherdstown and Millville (c)	0	7	32	77	145	219	297	358	397	404	382	326	261	196	142	103	76	57	45	39	33	31	29	27	26
		Total Storage in Major Watercourses(c)	0	70	261	532	786	947	1011	988	905	793	667	531	408	303	223	169	131	106	90	80	73	69	66	63	61
		Rate of Change of Storage (b)	0	261	462	529	415	225	41	-106	-195	-238	-262	-259	-226	-185	-134	-92	-63	-41	-26	-17	-11	-7	-6	-5	
		Inflow to Major Watercourses (b)	0	263	476	556	481	348	229	130	87	76	64	54	43	30	27	25	22	20	16	20	17	21	19	18	
		Σ Inflow to Major Watercourses (c)	0	71	266	548	829	1039	1181	1264	1311	1348	1382	1406	1429	1445	1459	1475	1487	1499	1509	1519	1528	1538	1548	1557	1566
	Minor	Storage in Minor Watercourses																									
		Above Shepherdstown (c)	0	268	526	655	600	445	290	169	97	81	70	56	43	36	34	27	27	27	25	25	22	20	25	22	
		Above Millville (c)	0	162	261	262	188	92	30	12	20	20	12	9	8	6	9	9	9	9	8	9	9	9	8	8	
		Below Shepherdstown and Millville (c)	0	90	170	225	250	223	200	118	77	67	62	57	47	25	15	18	10	5	0	8	3	15	8	8	
		Total Storage in Minor Watercourses(c)	0	520	957	1142	1038	760	520	299	194	168	144	122	98	67	58	54	46	41	33	42	34	44	41	38	
		Rate of Change of Storage (b)	1040	957	622	81	-382	-518	-461	-326	-131	-50	-46	-46	-55	-40	-13	-12	-13	-13	1	1	2	7	-6		
		Inflow to Minor Watercourses (b)	1040	1220	1098	637	99	-170	-232	-196	-44	26	18	8	-12	-10	14	13	9	7	17	21	19	28	13		
		Σ Inflow to Minor Watercourses (c)	0	591	1223	1690	1867	1799	1701	1563	1505	1516	1526	1528	1527	1512	1517	1529	1533	1540	1542	1561	1562	1582	1589	1595	

Index-gage for nearby ungaged areas. (b) 1,000 c.f.s. (c) 1,000 acre-feet. (d) Storage in Minor Watercourses = 2.5 x Inflow to Major Watercourses.

Table C--Data for Figure 3 (all values rounded from original data and computations)

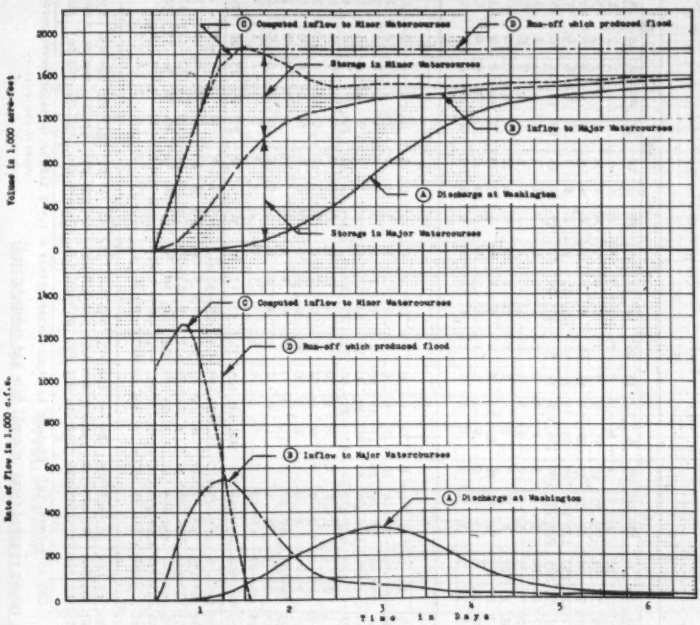
Volume in 1,000 acre-feet
Rate of Flow in 1,000 c.f.s.
Time in Days
C Computed inflow to Minor Watercourses
D Run-off which produced flood
Storage in Minor Watercourses
B Inflow to Major Watercourses
A Discharge at Washington
Storage in Major Watercourses

Fig. 3--Storage accounting for typical flood, Potomac River above Washington

Some mention of time and cost of preparation of the runoff-determinations will also aid in judging the merits of storage-accounting. The three illustrated computations, covering seven days of record each, utilized nine man-days of non-technical clerical personnel at $105 per month, whereas the alternative calculation required between 70 and 100 man-days of trained technical personnel averaging $250 per month. The preparatory work for the storage-accounting practice, if results like those illustrated are to be obtained, is laborious, since it requires a thorough unit-hydrograph analysis of the watershed, but its use is simple and applicable by personnel whose annual cost can be borne by almost any water-use agency.

U. S. Engineer Field Office,
Winchester, Virginia

DISCUSSION

E. T. SCHULEEN (Pennsylvania Water and Power Company, Holtwood, Pennsylvania)--Mr. CLARK presents a new approach to the problem of computing the runoff-volume or depth from a given storm. Through an ingenious application of flood-routing procedures in reverse, channel-storage as indicated by observed stages becomes an index of runoff. The usual methods of computing the runoff-volume by separating the base-flow from the total hydrograph do not permit any

Data		14				15				16				17				18				19				20			
Hour		6	12	18	24	6	12	18	24	6	12	18	24	6	12	18	24	6	12	18	24	6	12	18	24	6	12	18	24
Record of Discharges 1,000 c.f.s.	Burketown	0	0	1	2	6	17	41	24	12	8	6	4	4	3	3	2	2	2	2	2	1	1	1	1	1	1	1	1
	Lynwood	1	1	3	9	18	33	74	74	54	35	21	15	11	9	7	6	6	5	5	4	4	4	3	3	3	3	3	2
	Laney	1	1	1	3	26	56	78	96	98	77	53	33	20	14	11	10	8	7	7	6	6	5	5	5	4	4	4	4
	Front Royal	2	4	3	19	20	32	71	115	130	123	103	74	49	31	21	16	13	11	9	8	8	7	6	6	6	5	5	5
	Millville	4	7	12	15	37	63	67	90	165	227	227	190	146	108	77	51	33	26	22	19	17	15	14	12	11	10	10	9
	Grottoes	0	0	1	3	4	7	17	20	14	9	6	3	2	2	2	2	1	1	1	1	1	1	1	1	1	1	1	1
	Waynesboro	0	1	3	4	3	8	10	7	5	3	2	2	2	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0
	Cootes Store	0	0	2	10	11	30	38	21	12	8	5	3	2	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0
	Strasburg	1	1	2	5	6	8	17	27	53	97	48	26	18	13	8	6	5	4	4	3	3	3	3	2	2	2	2	2
	Winchester	1	2	2	6	11	14	22	10	6	3	2	2	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0
	Buckton	0	1	1	2	4	7	15	14	5	3	2	2	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0
Storage, Major Watercourses 1,000 acre-feet	Discharge x factor																												
	Burketown .10	0	0	0	0	1	2	4	2	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Lynwood .67	0	0	2	6	12	22	49	49	36	24	14	10	7	6	5	4	4	3	3	3	3	2	2	2	2	2	2	2
	Laney .88	0	1	1	2	23	49	68	85	86	68	46	29	17	12	10	8	7	7	6	6	5	5	4	4	4	4	3	3
	Front Royal .97	2	4	3	18	19	31	69	112	126	119	100	72	48	30	20	15	13	11	9	8	7	7	7	6	5	5	5	4
	Millville .75	3	5	9	11	27	47	51	67	124	170	170	143	110	81	58	39	25	19	17	14	12	11	10	9	9	8	8	7
	Grottoes .08	0	0	0	0	0	1	1	2	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Waynesboro .22	0	0	1	1	1	2	2	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Cootes Store .33	0	0	1	3	4	10	13	7	4	2	2	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Strasburg 1.03	1	1	1	6	8	17	28	54	100	49	27	19	13	9	7	6	5	4	4	3	3	3	3	3	2	2	2	2
	Winchester .63	1	1	1	4	7	9	14	7	3	2	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0
	Buckton 5.33 (a)	1	4	6	13	22	36	78	74	27	17	12	9	7	5	4	3	3	3	2	2	2	2	1	1	1	1	1	1
	Total Storage in Major Watersic d)	8	16	25	64	124	226	377	460	509	454	374	284	204	145	105	76	57	47	41	36	32	30	27	25	23	22	21	19
Total Flood Flow	Rate of Change of Storage (b)	13	17	48	98	161	254	235	132	- 6	-135	-171	-170	-140	-99	-54	-34	-29	-16	-12	- 9	- 6	- 5	- 5	- 3	- 3	- 3	- 2	
	Inflow to Major Watercourses (b)	16	24	60	114	198	316	302	222	159	92	57	20	6	9	23	17	4	9	10	10	11	10	9	9	8	8	8	
	Storage in Minor Watersic)	24	36	90	170	296	474	453	333	238	138	85	30	9	14	35	26	6	13	15	15	16	14	13	13	12	11	11	
	Storage, Major and Minor Watersic)	32	52	115	234	419	699	830	793	747	592	459	314	213	159	139	102	62	60	56	50	48	44	40	38	36	33	32	
	Rate of Change of Storage (b)	52	83	182	304	465	411	94	-83	-334	-288	-276	-246	-155	-74	-57	-77	-42	- 6	-10	- 8	- 7	- 8	- 6	- 4	- 5	- 4		
	Inflow to Minor Watercourses (b)	56	90	194	319	502	474	161	64	169	- 61	- 51	-56	- 9	34	20	-25	- 9	20	12	10	10	7	8	8	6	7		
	Σ Flow at Millville (c)	2	4	9	16	29	54	86	125	189	287	401	505	589	652	699	731	752	766	778	788	797	805	812	818	824	830	835	840
	Σ Inflow to Major Watercourses (c)	10	21	34	80	152	279	463	586	698	741	775	788	792	797	804	807	808	813	820	824	829	834	839	843	848	851	855	859
	Σ Inflow to Minor Watercourses (c)	34	56	124	250	448	753	916	918	936	879	859	819	802	811	837	833	813	826	834	838	845	849	852	856	860	863	867	

(a) Index gage for nearby ungaged areas. (b) 1,000 c.f.s. (c) 1,000 acre-feet. (d) Storage in Minor Watercourses = 1.5 x Inflow to Major Watercourses.

Table D--Data for Figure 4 (all values rounded from original data and computations)

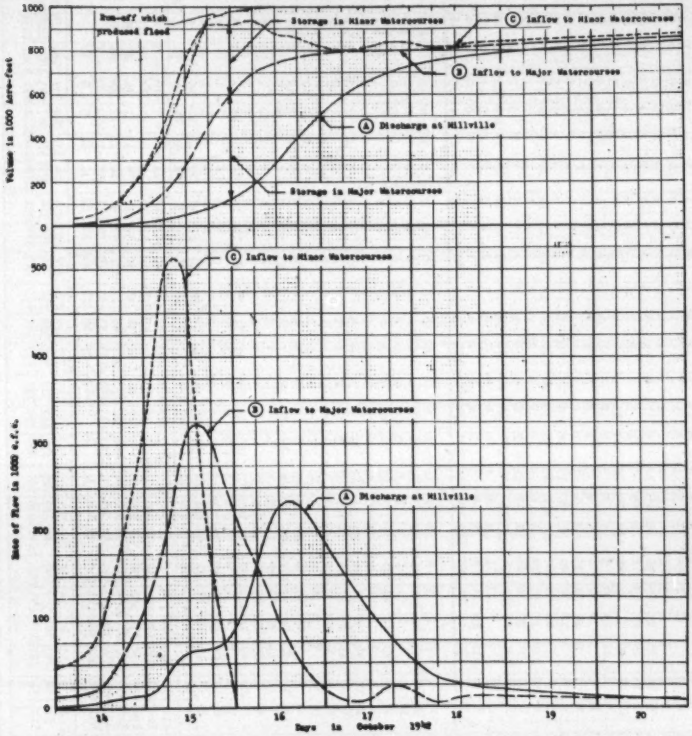
Run-off which produced flood
Storage in Minor Watercourses
C Inflow to Minor Watercourses
B Inflow to Major Watercourses
A Discharge at Millville
Storage in Major Watercourses
Volume in 1000 acre-feet
Rate of Flow in 1000 c.f.s.
Days in October 1942

Fig. 4--Storage accounting, Shenandoah River above Millville, October 1942

such determination to be made until after the end of the runoff-period; whereas, the proposed application of "storage-accounting" methods offers means of obtaining this value for each time-unit while the storm is in progress.

It should be recognized, however, that Mr. CLARK'S method involves the usual assumptions and attendant errors inherent in flood-routing computations. In addition, assumption is made of a constant relation between the storage in the minor watercourses and the outflow from this storage which becomes inflow to the major watercourses. It is in this step that the runoff-volume is determined by making it equal to the computed volume of inflow to the minor watercourses during the storm-period. The mass-curve of inflow to the minor watercourses dips down immediately after the end of the storm. This results from negative inflow to the minor watercourses and is interpreted as the effect of infiltration. As stated in the paper the infiltration during the storm has been deliberately obscured by overestimation of the constant expressing storage in the minor

Date		14				15				16				17				18				19				20			
Hour		6	12	18	24	6	12	18	24	6	12	18	24	6	12	18	24	6	12	18	24	6	12	18	24	6	12	18	24
Record of Discharge 1,000 c.f.s.	Bloomington (K.B.)	0	0	1	4	6	8	9	13	9	8	6	4	4	3	3	2	2	2	2	1	1	1	1	1	1	1	1	1
	Bloomington (S)	0	0	1	2	3	3	4	7	4	3	3	3	2	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0
	Franklin	0	1	1	1	3	3	5	3	2	2	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0
	Pinto	0	1	1	5	19	21	25	45	34	20	16	12	9	7	5	5	4	3	3	3	3	2	2	2	2	2	2	2
	Cumberland (W.C.)	0	4	4	6	11	19	21	13	8	6	5	4	3	3	2	2	2	2	1	1	1	1	1	1	1	1	1	1
	Cumberland	1	5	5	11	24	46	51	47	48	34	24	18	14	11	9	7	6	6	5	5	4	4	3	3	3	3	2	2
	Meadsville	0	1	1	3	8	11	14	15	8	5	4	3	2	2	1	1	1	1	1	0	0	0	0	0	0	0	0	0
	Petersburg	0	0	0	1	2	5	4	7	6	5	4	3	3	2	2	2	2	2	1	1	1	1	1	1	1	1	1	1
	Moorefield	0	0	0	1	3	9	20	18	15	7	4	3	2	2	2	1	1	1	1	1	1	1	1	1	1	1	0	0
	Springfield	0	1	1	4	7	18	33	40	37	30	17	12	9	6	6	6	6	5	5	4	4	3	3	3	3	2	2	2
	Paw Paw	1	3	10	15	24	37	61	96	109	110	102	85	58	39	28	22	18	16	13	12	11	10	9	8	7	7	6	6
	Yellow Spring	0	5	1	4	11	16	27	35	19	9	6	4	3	3	2	2	2	2	1	1	1	1	1	1	1	1	1	1
	Great Cacapon	0	0	1	6	10	19	27	38	46	51	37	22	12	8	6	5	5	4	3	3	3	2	2	2	2	2	2	2
	Hancock	1	1	1	6	27	50	81	110	134	153	157	145	124	98	82	42	32	26	22	19	17	15	13	12	11	10	9	9
	Fairview	0	0	1	2	3	6	7	10	11	9	8	7	5	4	4	3	3	3	2	2	2	2	2	2	1	1	1	1
	Meadsville	0	1	1	3	8	11	14	15	8	5	4	3	2	2	1	1	1	1	1	1	1	1	0	0	0	0	0	0
	Shepherdstown	2	2	2	3	7	30	81	124	158	183	198	200	192	174	147	110	73	51	41	34	29	26	23	21	19	17	16	15
Storage in Major Watercourses 1,000 acre-feet	Discharge x factor																												
	Bloomington (K.B.) .2	0	0	0	1	1	1	2	3	2	2	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Bloomington (S) .2	0	0	0	0	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Franklin .37	0	0	0	0	1	1	2	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Pinto .47	0	1	1	2	9	10	12	21	16	9	7	5	4	3	3	2	2	2	1	1	1	1	1	1	1	1	1	1
	Cumberland (W.C.) .09	0	0	0	1	1	2	2	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Cumberland .75	1	4	4	8	18	34	38	35	36	26	18	13	11	8	7	6	5	4	4	4	3	3	2	2	2	2	2	2
	Meadsville 1.75 (a)	0	1	2	6	14	19	25	27	13	9	7	5	3	3	2	2	2	2	1	1	1	1	1	1	1	1	1	1
	Petersburg .33	0	0	0	0	1	1	2	2	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0
	Moorefield .33	0	0	0	0	1	3	7	6	5	2	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
	Springfield .75	0	0	0	1	3	5	13	25	30	28	22	13	9	7	6	5	4	4	3	3	3	3	2	2	2	2	2	2
	Paw Paw .80	1	2	6	12	19	30	42	77	87	88	82	68	46	31	22	17	15	12	11	10	9	8	7	6	6	6	5	5
	Yellow Spring 1.20 (a)	0	6	2	5	13	19	32	42	22	11	7	5	4	3	3	2	2	2	1	1	1	1	1	1	1	1	1	1
	Great Cacapon .76	0	0	1	5	7	15	21	29	34	39	28	17	9	6	5	4	4	3	3	2	2	2	2	1	1	1	1	1
	Hancock .97	1	1	1	5	26	49	78	107	130	148	152	141	120	91	60	41	31	25	21	18	16	14	13	12	11	10	9	8
	Fairview .50	0	0	0	1	2	3	3	4	5	5	4	3	2	2	2	2	1	1	1	1	1	1	1	1	1	1	1	1
	Meadsville 1.88 (a)	0	1	2	6	15	21	28	29	15	10	7	5	4	3	3	2	2	2	1	1	1	1	1	1	1	1	1	1
	Shepherdstown .51	1	1	1	4	15	41	63	81	93	101	102	98	89	75	56	37	26	21	17	15	13	12	11	10	9	8	7	7
	Total Storage (c)	4	17	22	54	136	229	346	473	481	473	439	381	313	249	189	141	106	84	70	61	54	48	43	40	36	34	31	29
Total Flood Flow	Rate of change of storage (b)	17	18	36	114	175	209	244	135	0	-41	-92	-127	-118	-124	-108	-83	-57	-36	-23	-17	-13	-11	- 8	- 7	- 6	- 5	- 4	
	Inflow to Major Waters (b)	19	20	38	117	182	239	325	259	158	142	106	73	60	50	39	27	15	15	18	17	16	15	15	14	12	12	12	
	Storage in Minor Waters (c d)	43	44	86	262	409	538	731	582	356	319	239	169	135	112	88	61	34	35	40	39	37	34	33	31	28	27	26	
	Storage, Major and Minor (c)	47	61	108	316	545	767	1077	1055	837	792	678	546	448	361	277	202	140	119	110	99	91	82	76	71	64	61	57	
	Rate of Change of Storage (b)	61	61	254	437	651	532	289	-240	-263	-158	-246	-231	-185	-171	-159	-137	-83	-30	-20	-19	-17	-15	-11	-12	-10	- 7		
	Inflow to Minor Waters (b)	63	63	256	440	456	562	370	416	105	25	-46	-31	7	3	-12	-27	-10	21	21	14	12	11	12	9	9	10		
	Σ Flow at Shepherdstown (c)	0	1	2	3	6	15	42	94	164	249	344	444	542	633	713	777	822	854	876	895	910	924	936	947	957	966	974	982
	Σ Inflow to Major Waters (c)	5	18	24	57	142	243	388	567	645	722	783	825	855	882	902	918	928	938	946	956	964	972	979	987	993	1000	1005	1011
	Σ Inflow to Minor Waters (c)	47	62	110	319	551	781	1119	1149	1001	1041	1024	991	990	994	990	979	962	973	986	994	1001	1006	1012	1018	1021	1027	1031	

(a) Index gage for nearby ungaged areas. (b) 1,000 c.f.s. (c) 1,000 acre-feet. (d) Storage in Minor Watercourses = 2.25 x Inflow to Major Watercourses.

Table E--Data for Figure 5 (all values rounded from original data and computations)

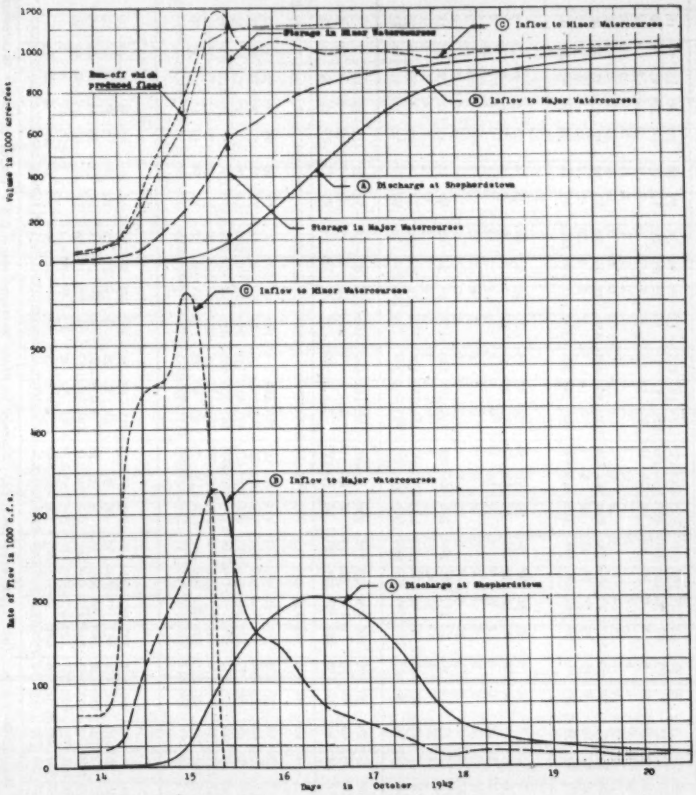
Volume in 1000 acre-feet
Rate of Flow in 1000 c.f.s.
Storage in Minor Watercourses
Run-off which Produced Flood
Ⓒ Inflow to Minor Watercourses
Ⓑ Inflow to Major Watercourses
Ⓐ Discharge at Shepherdstown
Storage in Major Watercourses
Ⓒ Inflow to Minor Watercourses
Ⓑ Inflow to Major Watercourses
Ⓐ Discharge at Shepherdstown
Days in October 1942

Fig. 5--Storage accounting, Potomac River above Shepherdstown, October 1942

watercourses, in order that the mass-curves of runoff and inflow might agree for the storm-duration. This appears contrary to the usual concept of a high infiltration-rate at the start of the storm with decreasing rates as the storm progresses. The curve of inflow-rate to the minor watercourses shown at the bottom of the charts indicates a high runoff-rate at the start of the storm and a decreasing rate during the storm, finally becoming negative after the storm ends. It is hoped that the author will clarify this point in his closure. While not specifically mentioned in the paper the term "runoff" includes surface-runoff, sub-surface runoff, and ground-water runoff. The mass-curves of inflow to minor watercourses, inflow to major watercourses, and the discharge at the drainage-area outlet will all ultimately reach the mass-curve of runoff.

			Date	14				15				16				17				18				19				20			
			Hour	6	12	18	24	6	12	18	24	6	12	18	24	6	12	18	24	6	12	18	24	6	12	18	24	6	12	18	24
Above Washington but below Shepherdstown and Millville	Record of Discharge 1,000 c.f.s.		Shepherdstown	2	2	2	3	8	30	81	123	158	184	200	200	192	174	147	111	73	51	40	34	29	26	23	21	19	17	16	15
			Millville	4	7	12	15	37	63	67	90	165	227	227	190	146	108	77	51	33	26	22	19	17	15	14	12	11	10	10	9
			Frederick	0	1	2	4	5	5	4	6	10	12	18	19	14	11	10	6	5	4	3	3	3	2	2	2	2	2	2	2
			Sharpsburg	0	0	0	0	1	1	1	1	2	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0
			Duckton	0	1	1	2	4	7	15	18	2	3	2	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0
			Point of Rocks	4	10	11	21	24	60	107	170	266	370	448	464	427	362	300	238	180	127	94	72	60	52	47	42	33	30	28	26
			Leesburg	3	8	10	11	9	8	19	34	45	25	12	8	6	4	4	3	2	2	2	2	2	2	1	1	1	1	1	1
			Washington	3	5	19	36	38	41	54	127	190	248	329	415	446	429	382	321	263	207	150	110	85	71	61	54	48	44	40	37
	Storage in Watercourses	Major	Discharge x factor																												
			Shepherdstown .29	1	0	1	1	2	9	23	36	46	54	59	59	56	51	43	33	21	15	12	10	9	8	7	6	6	5	5	4
			Millville .29	1	2	4	4	11	18	20	26	48	66	66	56	43	31	23	15	10	7	6	5	5	5	4	3	3	3	3	3
			Frederick .50	0	1	1	2	2	2	3	3	5	6	9	10	7	5	4	3	2	2	2	2	1	1	1	1	1	1	1	1
			Sharpsburg .29	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			Duckton .66(a)	0	0	1	2	3	5	10	9	3	2	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			Point of Rocks .66	3	7	7	14	16	40	71	112	176	244	296	306	282	239	198	157	119	84	62	48	40	34	31	22	22	20	18	17
			Leesburg .90 (a)	2	7	9	10	8	8	17	31	40	23	11	7	5	4	3	3	2	2	2	2	1	1	1	1	1	1	1	1
			Washington .38	1	2	7	13	14	15	20	48	72	93	123	155	167	161	143	121	99	78	57	41	32	27	23	18	18	16	15	14
			Total Storage (c)	8	19	30	46	56	97	163	266	390	488	566	594	561	493	415	332	253	188	141	108	88	76	67	51	51	46	43	40
		Minor	Rate of change (b)	19	22	27	26	50	106	169	228	223	176	108	- 5	-101	-146	-161	-162	-144	-113	-80	-52	-32	-21	-16	-16	-14	- 8	- 6	
			Inflow to Major (b)	17	19	33	44	44	55	74	141	90	13	7	20	7	1	- 4	- 4	14	18	8	5	8	9	9	4	4	8	8	
			Storage in Minor (c.d)	43	47	82	110	110	138	186	354	225	33	18	50	17	3	- 9	-10	34	44	19	14	19	23	23	11	10	21	19	
Total above Washington	Flood-Flow in Watercourse, Minor		Σ Flow at Washington (c)	1	3	9	23	41	61	85	130	209	319	463	649	865	1084	1286	1462	1606	1726	1815	1880	1929	1968	2001	2030	2055	2078	2099	2118
			Storage in Major																												
			Above Shepherdstown (a)	4	17	22	54	136	228	345	472	480	472	439	381	313	249	189	141	106	84	70	61	54	48	43	40	36	34	31	29
			Above Millville (a)	8	16	25	64	123	226	377	460	509	454	374	284	204	145	105	76	57	47	41	36	32	30	27	25	23	22	21	19
			Below Shep and Mill(a)	8	19	30	46	56	97	163	266	390	488	566	594	561	493	415	332	253	188	141	108	88	76	67	60	51	46	43	40
			Total Storage (c)	20	52	77	164	315	551	885	1198	1379	1414	1379	1259	1078	887	709	549	416	319	252	205	174	154	137	125	110	102	95	88
			Rate of Change (b)	52	57	112	238	387	570	647	494	216	0	-155	-301	-372	-369	-338	-293	-230	-164	-114	-78	-51	-37	-29	-27	-23	-15	-14	
			Inflow to Major (b)	55	62	131	274	429	611	701	621	406	248	174	114	74	60	44	28	33	43	36	32	34	34	32	27	25	29	26	
			Σ Inflow to Major (c)	21	55	86	187	356	612	970	1328	1568	1733	1814	1908	1943	1971	1995	2011	2024	2045	2067	2085	2103	2122	2138	2155	2165	2180	2194	2206
			Storage in Minor																												
			Above Shepherds (c)	43	44	86	263	407	538	731	583	356	320	241	166	135	112	88	61	34	35	40	39	37	34	33	31	28	27	26	
			Above Millville (c)	24	36	90	170	296	474	453	333	258	138	85	30	9	14	35	26	6	13	15	15	16	14	13	13	12	11	11	
			Below Shep and Mill (c)	43	47	82	110	110	138	186	354	225	33	18	50	17	3	- 9	-10	34	44	19	14	19	23	23	11	10	21	19	
			Total Storage (c)	110	127	258	543	813	1190	1370	1270	819	491	344	246	161	129	114	77	74	92	74	68	72	71	69	55	50	59	56	
			Rate of Change (b)	127	148	416	555	607	557	180	-551	-779	-475	-245	-183	-117	- 47	-52	-40	15	0	-24	- 2	3	- 3	-16	-19	4	6		
			Inflow to Minor (b)	182	210	547	829	1032	1166	821	70	-373	-227	- 71	-69	-43	13	- 8	-12	48	43	12	30	37	31	16	8	29	35		
			Σ Inflow to Minor (c)	131	182	344	730	1169	1762	2340	2596	2407	2224	2186	2154	2104	2100	2109	2088	2098	2137	2141	2153	2175	2193	2207	2210	2215	2239	2250	

(a) Index gage for nearby ungaged areas. (b) 1,000 c.f.s. (c) 1,000 acre-feet. (d) Storage in Minor Watercourses = 2.5 x Inflow to Major Watercourses.

Table F--Data for Figure 6 (all values rounded from original data and computations)

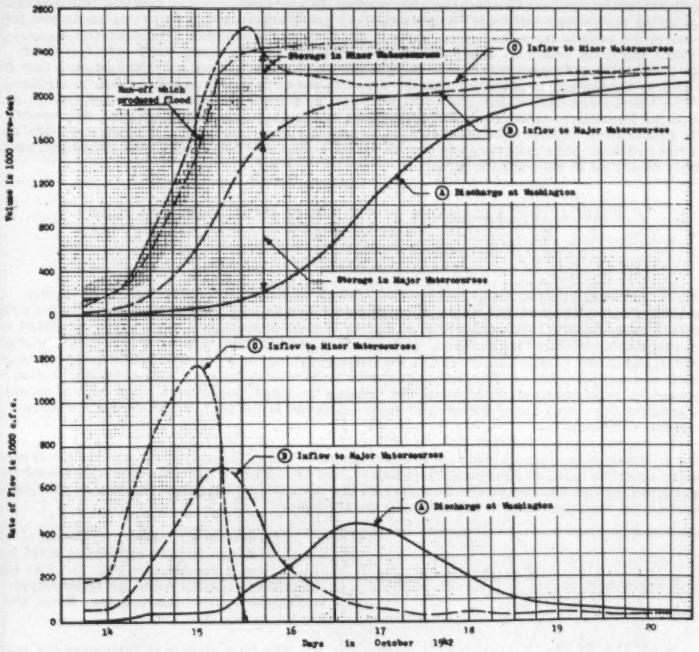

Fig. 6--Storage accounting, Potomac River above Washington, October 1942

The application of storage-accounting methods in the field of flow-forecasting is beyond the scope of Mr. CLARK'S paper. However, the ability to determine the runoff-depth during, or at least shortly after, the storm would be of great assistance to the flow-forecaster. When a forecast has been made on the basis of observed rainfall by unit-hydrograph, the forecaster is invariably faced with the necessity of adjusting his forecast hydrograph in the light of subsequent observed discharges at the forecast-point. Should the observed discharge be less than the predicted value, the estimated runoff may be too high or the time of peak predicted too early. Should the observed discharge be more than the predicted value the reverse may be true. Adjustments to the estimated runoff-depth by ratio of the observed to the predicted discharge-ordinates at a given time may result in serious errors. If Mr. CLARK'S method will give a reasonably accurate value of runoff-depth for each time period of the storm such adjustment of the forecast hydrograph could be made with more confidence.

C. O. CLARK (closure)--In his generous discussion, Mr. SCHULEEN asks for clarification of that part of the accounting procedure which results in a dip in the mass-curve of inflow to the minor watercourses immediately after the end of the storm. Each of the mass-curves of inflow is merely the mass-curve of outflow plus storage-quantities in the major watercourses and in the minor watercourses (including the smallest of water-carrying channels and therefore the surface-area of the contributing watershed) but not the storage below the ground. Since the mass-curve of runoff which produced the flood includes total runoff, there is properly an ordinate of storage in ground-water between it and the mass-curve of inflow to minor watercourses. It is

this ordinate which has been deliberately obscured by overestimation of the constant expressing storage in the minor watercourses. While the author has freely admitted that some portion of the mass-curve dip results from theoretical errors, nevertheless it would be a mistake also to assume that a dip is not possible. Since natural watercourses are pervious, water may flow from storage in the watercourses to storage in the ground-water. The amount or nature of such flow in large natural watersheds is not understood as the evidence of it is always confounded by surface-flow. The unit-hydrographs illustrated in Figures 1 to 3, derived by the method presented by the author in the November, 1943, issue of Transactions of the American Society of Civil Engineers, contain a theoretical volume equivalent of 70 per cent pure surface-runoff and 30 per cent flow by non-surface routes. Such arbitrary division is possible only in a unit-hydrograph and cannot be positively identified in natural hydrographs.

A FORECASTING TECHNIQUE FOR ROUTING AND COMBINING FLOW IN TERMS OF STAGE

Max A. Kohler

The close relationship existing between the "change in stage", properly lagged, at various points along a major stream such as the Mississippi River has long been recognized. Forecasting procedures based on this relationship and consisting of lists of empirical rules have been found to yield commendable results for reaches involving only slight tributary inflow. For a reach entered by several significant tributaries, however, the rules required for a reliable procedure become so numerous and complex that considerable experience is necessary to their successful application. The procedure to be discussed is based on the "change-in-stage" relationship and may be considered a graphical presentation of established rules employed in the past, which have not usually been used in combination.

The following data are required for the development: (1) A rating-curve for one station (above backwater from the main stream) on each tributary; and (2) stage-records at all selected stations. Rating-curves for the stations on the main stream are not indispensible, but they are of considerable assistance when the reach is affected by tributary inflow.

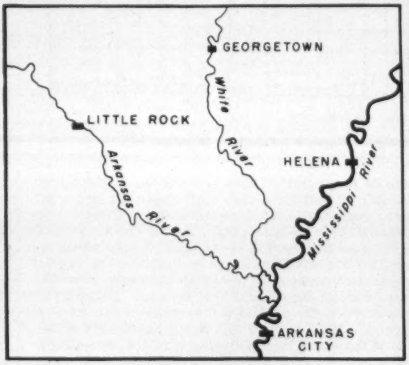

Fig. 1--Map of Helena-Arkansas City Reach of Mississippi River

The Helena-Arkansas City Reach of the Mississippi River has been selected for illustrative purposes (see Fig. 1). Two significant tributaries enter the Mississippi within this reach--the Arkansas River and the White River.

The first step is to determine the approximate minimum crest travel-time through the reach, which is found to be about two days from Helena to Arkansas City. If the travel-time from Helena to Arkansas City is assumed to be two days, it would seem logical that the change in stage at Helena for any two-day period should be a good index to the change at Arkansas City the following two days, particularly if tributary inflow is relatively constant. Further, because of variations in the rate of increase of storage with respect to stage, it might be expected that the effect of a given change at Helena on the corresponding change at Arkansas City depends upon the stage at which the change takes place. In accordance with this line of reasoning the stage at Arkansas City for a particular day has been plotted against the stage at Arkansas City two days later with the change at Helena during the past two days as a parameter, and a family of curves constructed (see Fig. 2-A). The data plotted were, of course, for selected periods when the tributary inflow was relatively constant.

It will be noted that the family of curves consists of straight parallel lines. The plotted data

seemed to indicate that changes occurring at stages of 25 to 35 feet do not "carry through" as completely as those occurring at stages outside of this range. This effect appeared to be too slight, however, to justify curvature.

For a reach involving no tributary inflow, this family of curves would ordinarily suffice and the desired portion of the hydrograph would be routed through the reach in the customary manner. Two tributaries enter the Helena-Arkansas City Reach, however, and must be given consideration.

Little Rock was selected as an index-station for the Arkansas River. Since the average time of travel between Little Rock and Arkansas City is approximately two days, the change in discharge

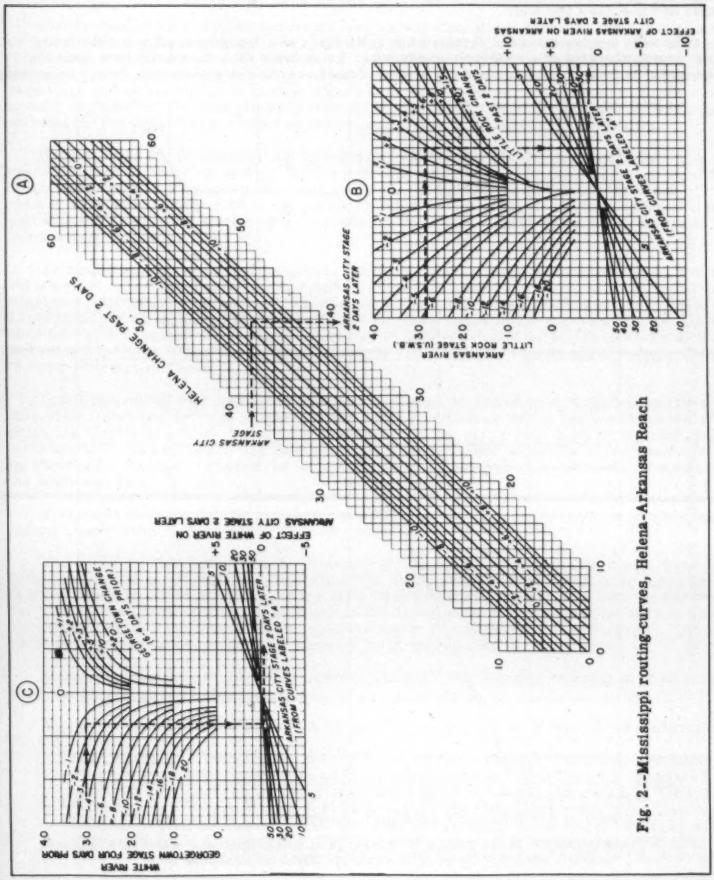
A
B
C
HELENA CHANGE PAST 2 DAYS
ARKANSAS CITY STAGE
ARKANSAS CITY STAGE 2 DAYS LATER
LITTLE ROCK STAGE
ARKANSAS RIVER
LITTLE ROCK STAGE (U.S.W.B.)
EFFECT OF ARKANSAS RIVER ON ARKANSAS CITY STAGE 2 DAYS LATER
ARKANSAS CITY STAGE 2 DAYS LATER (FROM CURVES LABELED 1)
WHITE RIVER
GEORGETOWN STAGE FOUR DAYS PRIOR
EFFECT OF WHITE RIVER ON ARKANSAS CITY STAGE 2 DAYS LATER

Fig. 2--Mississippi routing-curves, Helena-Arkansas Reach

at Little Rock during any two-day period should be a reasonably sensitive index to that portion of the change in discharge at Arkansas City during the following two days attributable to the Arkansas River. In terms of stage, however, the effect at Arkansas City of a given change at Little Rock will depend upon the stage at both Little Rock and Arkansas City.

All changes in stage at Little Rock were first made comparable by introducing a variable representing the stage at Little Rock as shown in the upper set of curves of Figure 2-B. The horizontal axis of this chart is change in discharge. The axis has not been labeled in the Figure, however, because it has no significance once the curves are developed. The curves were derived directly from the rating-curve for Little Rock. For example, points along the plus two-foot change-curve were determined by finding the change in discharge when the river is at various stages and has risen two feet.

Data were then selected for periods when Little Rock was changing rapidly and the White River was discharging at a relatively steady rate. From these data, forecasts were made for Arkansas City from Figure 2-A and the errors of the forecasts were computed. Then, considering

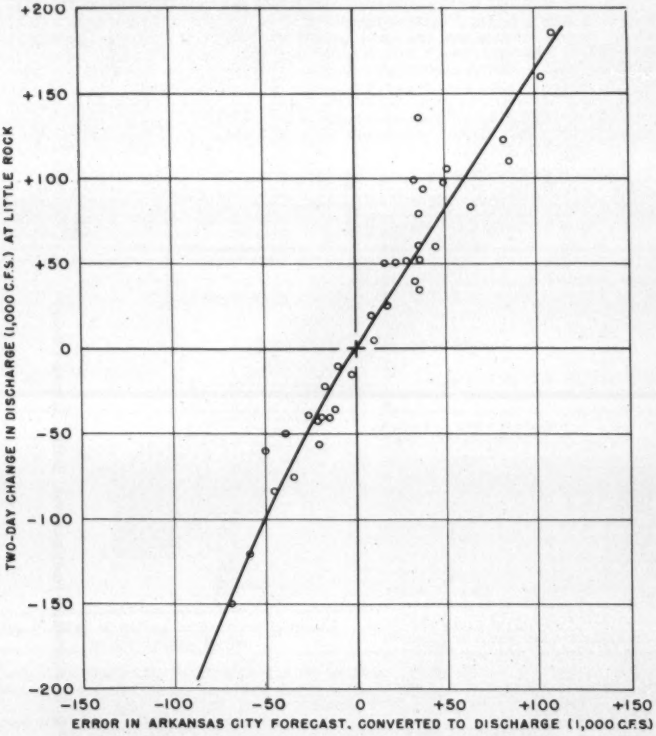

Fig. 3--Relationship between change in discharge at Little Rock and effect of Arkansas River upon discharge of Mississippi River at Arkansas City

that these errors were caused by variations of inflow from the Arkansas River, they were converted to discharge and plotted against the corresponding change in discharge at Little Rock (see Fig. 3). The curve drawn to best fit these points defines the relationship between the change in flow at Little Rock and the effect of the Arkansas River upon the discharge at Arkansas City.

The lower set of curves in Figure 2-B were then developed to conform with the horizontal discharge-axis of the upper set of curves by use of the Arkansas City rating-curve and the curve shown in Figure 3. For example, an increase in discharge of 100,000 cfs at Little Rock will apparently increase the flow at Arkansas City by 61,000 cfs (Fig. 3). The rise in feet for this increase in discharge at various stages was determined from the Arkansas City rating-curve. These corrections were then plotted at a 100,000 cfs Little Rock change in discharge (Fig. 2-B).

Georgetown, which is approximately six days' travel-time above Arkansas City, was selected as an index-station for the White River. A station of two days' travel-time would have been preferable, but stations this close to Arkansas City are at times within the backwater-influence of the main stream. The Georgetown correction-curves in Figure 2-C were developed in the same manner as the curves for Little Rock in Figure 2-B. Since Georgetown is six days above Arkansas City, however, the Georgetown change six to four days prior to the current day was used as an index for the White River's effect on the following two-day change at Arkansas City.

General rules for determining the independent variables for the development of this type of procedure may be stated as follows: (1) The period of all changes to be used as indices should be of the same length, and should be approximately equal to time of travel through the reach of the main stream; and (2) the period of any change to be used as an index should be in advance of the period at the downstream station by a time equal to the travel-time from the index-station to the lower end of the reach.

As mentioned previously, rating-curves for the main stream are not indispensable. The development of correction-curves for a tributary without the use of a main-stream rating-curve consumes less time, but the method requires more data for the same reliability. In the case of Little Rock, for example, the errors (in feet) of forecasts based on the curves in Figure 2-A could have been plotted against the change in discharge at Little Rock and the points labeled with the Arkansas City stage. Then the lower set of curves could have been drawn directly, by-passing the step indicated in Figure 3.

It will be recalled that the curves in Figure 2-A were developed from a limited portion of the data since it was necessary to exclude periods when the tributary inflow was not constant. At this point, the previously excluded data were introduced into the correlation using an adjusted stage at Arkansas City two days later--the adjusted stage being the actual minus the corrections indicated by Figures 2-B and 2-C. The curves for the change at Helena were then revised on the basis of the additional data.

Previously excluded data were introduced into the correlation for Little Rock in a similar manner, and the correction-curves revised accordingly.

The use of the final procedure, as developed for the Helena-Arkansas City Reach, involves three separate steps: First, from Figure 2-A, the determination of the forecast for Arkansas City two days hence based on the change in the main stream; second, from Figure 2-B, the correction (or modification) to be applied for the effect of the Arkansas River; and third, from Figure 2-C, the determination of the correction (or modification) to be applied for the White River. The algebraic sum of these values is the final forecast for Arkansas City two days hence.

Sample forecast computations are shown in Table 1. The following example is given to illustrate the method of computing forecasts.

Example--To forecast the stage at Arkansas City on May 27, as of May 25, on the basis of the data listed in Table 1

(1) Enter Figure 2-A from the left with 37.6, the current Arkansas City stage, and follow to the right to the intersection with +1.7, the Helena change. Read 38.8, the Arkansas City stage two days later, on the lower scale and enter this value in Column (9) of Table 1.
(2) Enter Figure 2-B from the left with 28.6, the current Little Rock stage, and follow to the right to the intersection with +2.8, the Little Rock change. Then follow vertically downward to 38.8, the Arkansas City stage two days later as determined from Figure 2-A. Read +1.0, the effect of the Arkansas River upon the Arkansas City stage two days later,

Table 1--Sample sheet forecast-computation

Date of computations	Forecast for date	Arkansas City stage	Helena change past 2 days	Little Rock		Georgetown		Arkansas City stage 2 days later			
				Stage	Change past 2 days	Stage 4 days prior	Change 6-4 days prior	From "A"	From "B"	From "C"	Total
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
1943	1943										
May 25	May 25	37.6	+1.7	28.6	+2.8	30.0	-1.3	38.8	+1.0	-0.4	39.4
	27	(39.4)	+1.7	30.0	+1.4	29.0	-1.0	40.7	+0.5	-0.2	41.0
	29	(41.0)	+1.6	29.6	-0.4	29.2	+0.2	42.3	-0.1	+0.1	42.3
	31	(42.3)	+1.7	28.4	-1.2	29.2	0.0	43.5	-0.4	0.0	43.1

from the scale on the right and enter this value in Column (10).

(3) Enter Figure 2-C from the left with 30.0, the Georgetown stage four days prior, and follow to the right to the intersection with -1.3, the Georgetown change. Then follow vertically downward to 38.8, the Arkansas City stage two days later as determined from Figure 2-A. Read -0.4, the effect of the White River upon the Arkansas City stage two days later, from the scale on the right and enter this value in Column (11).

(4) A stage of 39.4, the algebraic sum of Columns (9), (10), and (11), would then be forecast for Arkansas City on May 27.

The advance period of the forecast can then be extended in a similar manner by using forecast values of the variables.

Table 2--Verification of Arkansas City forecasts

Date	Actual Arkansas City stage	Forecasts Advance period in days							
		2		4		6		8	
		Stage	Error	Stage	Error	Stage	Error	Stage	Error
1944									
Mar. 4	24.4	...	...	...	...	...	...	...	...
5	25.7	...	...	...	...	...	...	...	...
6	26.6	...	...	...	...	...	...	...	...
7	27.1	...	...	...	...	...	...	...	...
8	27.4	...	...	...	...	...	...	...	...
9	27.7	...	...	...	...	...	...	...	...
10	27.9	...	...	...	...	...	...	...	...
11	28.1	...	...	...	...	...	...	...	...
12	28.2	28.3	-0.1	28.6	-0.4	29.3	-1.1	29.7	-1.5
13	28.3	28.4	-0.1	28.6	-0.3	28.9	-0.6	30.0	-1.7
14	28.4	28.4	0.0	28.5	-0.1	28.8	-0.4	29.0	-1.1
15	28.5	28.6	-0.1	28.7	-0.2	28.9	-0.4	29.2	-0.7
16	28.5	28.7	-0.2	28.7	-0.2	28.8	-0.3	29.1	-0.6
17	28.4	28.6	-0.2	28.7	-0.3	28.8	-0.4	29.0	-0.6
18	28.4	28.4	0.0	28.6	-0.2	28.6	-0.2	28.7	-0.3
19	28.5	28.1	+0.4	28.3	+0.2	28.4	+0.1	28.5	0.0
20	28.7	28.6	+0.1	28.6	+0.1	28.8	-0.1	28.8	-0.1
21	29.0	29.0	0.0	28.6	+0.4	28.8	+0.2	28.9	+0.1
22	29.5	29.1	+0.4	29.0	+0.5	29.0	+0.5	29.2	+0.3
23	29.9	29.1	+0.8	29.1	+0.8	28.7	+1.2	28.9	+1.0
24	30.1	29.7	+0.4	29.3	+0.8	29.2	+0.9	29.2	+0.9
25	30.5	30.2	+0.3	29.4	+1.1	29.4	+1.1	29.0	+1.5
26	31.0	30.8	+0.2	30.4	+0.6	30.0	+1.0	29.9	+1.1
27	31.5	31.5	0.0	31.2	+0.3	30.4	+1.1	30.4	+1.1
28	31.9	32.1	-0.2	31.9	0.0	31.5	+0.4	31.1	+0.8
29	32.3	32.6	-0.3	32.6	-0.3	32.3	0.0	31.5	+0.8
30	32.5	32.9	-0.4	33.1	-0.6	32.9	-0.4	32.5	0.0
31	32.7	33.0	-0.3	33.3	-0.6	33.2	-0.5	33.0	-0.3
Apr. 1	32.8	32.7	+0.1	33.1	-0.3	33.3	-0.5	33.1	-0.3
2	32.7	32.5	+0.2	32.8	-0.1	33.1	-0.4	33.0	-0.3
Absolute sum			4.8		8.4		11.8		15.1
Average error			0.22		0.38		0.54		0.69

In order to indicate the reliability of the procedure, two-, four-, six-, and eight-day forecasts have been computed for March 12 to April 2, 1944, and are tabulated, with the resulting errors, in Table 2. Actual upstream data were used throughout the computations; therefore, only the two-day forecasts may be considered as representative of actual forecasts.

U. S. Weather Bureau,
Washington 25, D. C.

DISCUSSION

FRANKLIN F. SNYDER (Office, Chief of Engineers, Washington, D. C.)--Through the use of a supplementary relationship for each tributary entering between two routing- or forecast-stations on the main river, the author has presented a technique for evaluating the individual tributary effect on the stage of the lower main-river station. The adjustments are logical ones and they have been developed through dual use of stage-increments and rating-curves although the rating-curves are not essential.

When rating-curves are available for all the stations involved, the possibility suggests itself of using relationships such as that of Figure 3 directly in determining the effect of the Arkansas River on the Arkansas City stage rather than developing the curves of Figures 2-A and 2-B. However, stages would have to be used where rating-curves were not available and the writer's experience indicates that stage-relations can often be extrapolated more successfully than rating-curves. In the case of a leveed river, such as the lower Mississippi, extrapolations of any kind must be made with caution.

Figure 3 indicates that changes in discharge on the Arkansas River at Little Rock carry through to the Arkansas City gage to a greater extent on rising stages as compared to falling stages. The actual result in terms of stage, of course, depends on the rating-curves. Except at low stages on the main river, the curves at the bottom of Figures 2-A and 2-B indicate little difference in the effect of rising or falling tributary-discharge on the main-river stage-correction. One item which might affect the results obtained with the procedure is that the storage-reduction applied to changes in tributary-discharge has been assumed constant, regardless of the existing stage.

The factors correlated by the author cover the principal items to be considered. In some cases an item which might affect the accuracy of corrections for tributary effect obtained with the procedure would be the existence of a variable stage-discharge relation at the lower main-river station. Such a condition would require two sets of curves instead of one, as presented at the bottom of Figures 2-A and 2-B, that is, one for rising and one for falling main-river stages.

RIVER-DISCHARGE IN BRAZIL, SOUTH AMERICA

Clarence S. Jarvis

For many years the abundance of water-resources in Brazil and the sparsity of published basic data related to runoff have presented an inviting challenge in the field of applied hydrology. Recently increased facilities whereby the actual river-gagings are recorded at many stations, apparently according to the best standards attainable and closely approaching methods adopted in this country, have done much to remove the uncertainties attaching to the early estimates, derivations, and occasional stream-discharge measurements in Brazil. According to the Hydroelectrical Power Bulletin No. 1 of the Brazilian government [see 1 of "References" at end of paper], dated 1940, the number of river-gaging stations maintained by that Government had increased from about 300 in 1930 to 1,730 in 1939; as of 1933, 107 were on the Rio Grande, nine on the Iguassu (or Curitaba), and 22 on other tributaries or main channels of the Parana River-System, 102 on the San Francisco River, and only 37 were in the Amazon Drainage-Basin. Naturally, attention has been concentrated largely on the discharge of rivers within convenient range of the metropolitan centers, such as São Paulo with population officially reported as 1,167,900 and with prospects for continuance of its phenomenal growth; and Rio de Janeiro, population as of 1940, published as 1,801,800. As an example, the Parahyba River, draining the hinterland of the metropolis on a northeasterly course to its mouth at Campos, some 200 miles northeast of Rio de Janeiro, and descending from its headwaters elevation of more than 3,000 feet in a 500-mile length of channel with a mean discharge of nearly 34,000 cubic feet per second throughout the years of available record at the Campos Bridge, is of such economic importance as to justify the establishment and

maintenance of 60 meteorological and 30 stream-gaging stations in 1939.

Probably the more recent growth of interest in the conservation and development of their water-resources may be illustrated by the statistics on stream-gagings on the Rio Grande and neighboring tributaries of the Parana River-System, which show 531 gagings at 163 stations recorded for 1938 as contrasted with totals of 1,002 gagings at 318 stations during the year 1941. The present-day installations of hydroelectric power-plants represent more than 25 per cent of the reported power-potentialities within convenient range of São Paulo, and nearly 60 per cent of the nearby resources for Rio de Janeiro, as contrasted with less than ten per cent for all of Brazil, (comprising an area some eight per cent greater than that of the United States of America, along with about one-third of both population and potential water-power).

Table 1 presents some of the salient data representing a summation of the most nearly authoritative and official records, estimates, derivations, and interpretations resulting from a fairly comprehensive research, extending at intervals over several years. It is not surprising that some conflicts of basic data have been encountered; without the recent releases of seemingly trustworthy basic hydrologic data, observed and processed closely in accordance with the best modern practice and standards, it would have been difficult if not impossible to reconcile the outstanding differences.

Examples of divergent behavior of tributaries are afforded by the Madeira River's headwaters in Bolivia. There, the Beni Branch, with a drainage-area about 70 per cent of either the Guapore or the Mamore, is credited with both a mean discharge and a flood-peak about equal to the totals from the other two tributaries. The evident explanation involves both excess precipitation and slope for the Beni, as it drains Andean regions ranging up to more than 20,000-foot elevation, while the other two branches drain the plateaus and grassy plains of Matto Grosso to the eastward.

Familiar examples of fully as marked differences in runoff-yield are provided by either the Ohio or the Tennessee river-systems in contrast with some of the tributaries of the Missouri or Arkansas with their sources and principal drainage-areas within the Great Plains.

The writer's quest for basic hydrologic data on the principal rivers of South America continued with but meager results for nearly 20 years, when he found transcripts of some of the records while back in the stacks of one of the prominent libraries of this city, on other research. He then informed the Assistant Librarian that there seemed to be at least ten volumes in the stacks for every one readily located in the card-index files lists; and he learned that this condition was generally recognized--samples of the voluminous records can be located readily by reference to the cards. Following up such clues, the writer has located literally scores of volumes, pamphlets, and other forms of technical publications which have furnished isolated station-records here and there, and fairly complete coverage for those basins in which either hydroelectric power- or irrigation-developments have emphasized the importance of systematic hydrologic studies.

If all references were listed in connection with each item of basic data utilized in the preparation of Table 1, such a bibliography might outweigh the textual material, particularly because of the fragmentary or intermittent nature of the earlier data, the unequal periods ordinarily covered by rainfall- and runoff-records, and the inevitable variety of interpretations and translations that crop up in the various commentators' renderings. A precedent has been established in this field by Dr. H. HELM CLAYTON [7] at the beginning of each volume on "World weather records", published by the Smithsonian Institution in 1927 and 1934, by relying on the inscription, "Collected from official sources". These volumes have been the most valuable references thus far discovered on temperature- and precipitation-data in not only South America, but also many other foreign countries.

Because of the variety of records and renderings encountered, whereby relatively few of the lines in Table 1 could be filled from single official sources, it was found inexpedient to discriminate between strictly official data and those partially dependent on derivations and presumably estimates, yet all listed on an equal footing elsewhere. For example, it is impossible to determine from the context of MAURICE PARDE'S paper [3] just what items depend strictly upon official records, or what variation has resulted from unequal weighting of individual station-records. However, convincing proof of his factual knowledge and the logic of his approach is to be found in the results he published concerning the mean annual precipitation and runoff pertaining to river-systems of many countries, including the Hudson, Delaware, Susquehanna, Potomac, Mississippi, Ohio, and several tributaries of the last two systems. Although they were unknown to the writer until some time after the publication of the discharge-data for the Ohio and Mississippi rivers in recent technical papers, PARDE'S results were generally fairly satisfactory and in reasonably close agreement with those released by the writer [8, 9]. Such results naturally lend some weight to PARDE'S generalizations

Table 1--Precipitation- and runoff-characteristics of selected rivers in, or adjacent to, Brazil, South America

River	Drainage-area	Main record period	Annual Precipitation, P			Annual runoff, R[a]				Mean C[b] =	Daily runoff		Variation (Max./Mean) = V	Modified Meyers rating	(P-R)
			Min.	Mean	Max.	Min.	Mean		Max.		Mean	Max.			
	sq mi	years	in	in	in	in	in	csm	in	pct	cfs	cfs		pct	in
Iguassu or Curitaba	24,000	1870-1940	36	65	96	16	34	2.48	50	52	59,500	350,000	5.9	22.6	31
Verde	1,580	1928-1940	49	84	118	34	61	4.43	82	72	7,000	56,000	8.0	14.1	23
Sapucar	3,120	1928-1940	53	86	124	36	66	4.78	86	76	14,900	85,000	5.7	15.6	20
Pardo	4,760	1928-1940	34	57	78	9	15	1.08	25	26	5,140	40,000	7.8	5.8	42
Mogi-Guassu	3,820	1928-1940	30	48	70	8	13	0.96	22	28	3,670	31,000	8.4	5.0	35
Grande	6,050	1928-1940	56	92	130	33	77	5.51	93	83	33,300	170,000	5.1	21.8	15 (?)
Grande	45,700	1928-1940	29	51	69	10	23	1.67	35	45	76,400	394,000	5.2	18.4	28
Grande, Parana Jct.	55,200	1928-1940	28	49	67	10	22	1.60	34	45	88,500	420,000	4.7	17.9	27
Paranahyba	100,000	1923-1940	41	56	70	14	21	1.54	33	37	154,000	480,000	3.1	15.2	35
Parana	187,000	1923-1940	38	50	66	10	17	1.24	28	34	232,000	700,000	3.0	16.2	33
Parahyba	22,500	1923-1930	42	54	69	15	20	1.50	25	37	33,700	152,000	4.5	10.1	34
San Francisco	280,000	1901-1940	34	45	58	9	16	1.14	26	35	319,000	870,000	2.7	16.4	29
Parnahyba	190,000	1901-1940	40	57	75	14	22	1.62	34	39	308,000	900,000	2.9	20.7	35
Tocantins	323,000	1912-1922	41	59	84	14	20	1.49	32	34	480,000	1,200,000	2.5	21.1	39
Xingu	232,000	1912-1922	36	52	70	11	15	1.12	24	29	260,000	860,000	3.4	17.8	37
Tapajos	166,000	1912-1922	37	51	68	11	16	1.14	24	30	190,000	700,000	3.7	17.2	35
Guapore	87,400	1873-1922[c]	26	42	63	6	10	0.76	16	25	66,000	181,000	2.7	6.1	32
Mamore	89,800	1873-1922	30	47	71	9	13	0.99	21	29	89,000	248,000	2.8	8.3	34
Beni	63,600	1873-1922	43	65	90	23	33	2.40	48	51	153,000	462,000	3.0	18.3	32
Madeira	482,500	1873-1922	34	53	74	11	19	1.39	30	36	670,000	1,810,000	2.7	26.0	34
Purus	154,400	1912-1922	26	42	66	8	14	1.00	21	32	155,000	600,000	3.9	15.3	28
Jurua	92,600	1912-1922	35	54	75	12	19	1.40	30	35	130,000	550,000	4.2	18.1	35
Headwaters	888,350	1912-1922	33	53	77	13	28	2.08	43	53	1,851,000	4,800,000	2.6	51.0	25
Negro	386,000	1912-1922	30	46	66	7	11	0.83	17	25	320,000	1,000,000	3.1	16.1	35
Trombetas	47,900	1912-1922	36	49	72	9	14	1.00	22	28	48,000	250,000	5.2	11.4	35
Amazon, at Manaos	1,320,000	1912-1922	40	56	78	17	25	1.86	38	45	2,450,000	7,200,000	2.9	62.6	31
at Obidos	1,945,000	1873-1922	44	62	87	15	21	1.54	35	34	3,000,000	8,300,000	2.8	59.5	41
at Mouth	2,772,000	1873-1922 [c]	47	64	94	14	19	1.42	32	30	3,950,000	9,100,000	2.3	54.6	45

[a] Runoff in inches depth over the drainage-area. [b] Percentage of rainfall observed in runoff. [c] There are breaks in the records.

and analyses of rainfall and runoff on the Amazon and neighboring river-systems. The writer is inclined to accord much weight to such results, in the same manner as that displayed when he discovered a complete year of discharge-records for the Delaware at Yardley, Pennsylvania, near Trenton, New Jersey. He incorporated this year of isolated record, 1886, with the other official and derived hydrographs of the Delaware River-System, despite the challenges of those who seemed more interested in the type of current-meter employed, and exact procedure used in the river-gaging, than in the name of the observer, MANSFIELD MERRIMAN, an able and distinguished engineer of the War Department in the Corps of Engineers.

To illustrate the problems encountered even when depending solely on officially sponsored and published records, attention is invited to the sixth item in Table 1. Realizing that the upper region of the Rio Grande comprises the Verde, Sapucar, and unnamed tributaries, with drainage-areas of 1,580, 3,120, and 1,350 square miles, respectively, it is readily seen that the yield alleged for the Rio Grande at that headwaters station, 5.51 csm, is probably 20 per cent too high, in view of the yields of 4.43 and 4.78 csm as published for the two tributaries above named. The unnamed tributaries would have to yield 8.52 csm in order to boost the yield of the 6,050 square miles to 5.51 csm; not an impossibility in the neighborhood of Alto de Serra with its mean annual rainfall-depth of 143 inches and its recorded maximum of 219 inches in one calendar year, but rendered highly improbable in view of the yield of the named tributaries and the observed rainfall at several stations within the drainage-area. With only 92 inches of mean annual rainfall derived from actual records for the basin, the alleged runoff of 77.0 inches per year invites challenge and explanation. While not an impossibility--precedents are to be found in both the Alps and the high Andes as well as Pyrennes--a difference of 15.5 inches between precipitation and runoff seems to be considerably too low. It was deemed best to copy those officially sponsored records of recent date rather than to reduce the quantities for the upper Rio Grande, and to point out the inconsistency among those headwaters-data as a practical example of what is encountered in greater measure among some of the earlier records, and of course reconciled before inclusion in the tabulation, thus being at once corrected and demoted to unofficial status, and rendering the term meaningless.

Taking into account both the number and apparent quality of basic hydrologic records available for incorporation in Table 1, the writer would rate the tabulated results in the order of their probable reliability as follows: Lower Rio Grande; Parahyba; San Francisco; Tocantins; Madeira; Negro; Tapajos; Trombetas; Xingu; headwaters and minor tributaries of the Amazon; Parana; and Amazon.

Reference to physiographic, geographic, and topographic maps and also to isopluvial charts may afford some explanation of the divergent habits of neighboring tributaries; for example, the Rio Negro in contrast with neighboring headwaters. Evidently the distance inland, the topography, the prevailing winds and shadow effects on the leeward slopes of prominent barriers, the slope of drainage basins, the vegetal growth and other means of inducing infiltration or otherwise retarding runoff, all have a bearing on the final result, as manifested in river discharge and its variation.

Because of the intermittent records relating to some of the stations and drainage basins, and also because of considerable uncertainty attaching to the quality of early records or estimates, whichever they may have been, as well as some questions regarding the representative value of isolated station records in extensive regions, it is well to bear in mind that the writer makes no claims as to the relative values tabulated herewith. They merely represent the best solutions that could be secured from the basic data at hand.

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DISCUSSION OF PAPER "PRELIMINARY REPORT ON ANALYSIS OF RUNOFF RESULTING FROM SIMULATED RAINFALL ON A PAVED PLOT" BY C. F. IZZARD AND M. T. AUGUSTINE

W. I. Hicks

The increased use of large areas of flat paved and sodded surfaces not only in airport-construction but in express highways, parking-lots, roofs of large buildings, etc., makes desirable the hydraulic investigation which Messrs. IZZARD and AUGUSTINE have reported as accomplished and projected for future experimentation [see 1 of "References" at end of paper]. They are to be commended for the precision of experimental measurements on the smooth, plane surface which is the base from which the investigation will be expanded to include the rougher-paved and sodded surfaces which prevail in actual practice. (Note: Attention is called to an error in printing the line following equation (11) where "(p/43560d)" should read "(p ℓ/43560d)".

In connection with an investigation of urban runoff [2], the writer made a series of tests of plane-surface runoff on tar and sand-surface, tar and gravel-surface, and clipped-sod surface [3]. Sample test-runs are shown in Figure 1, in which one gallon per minute on 96 square feet equals one inch per hour of rainfall and of runoff. For detention at equilibrium-flow for these tests, we have equations (1), (2), and (3).

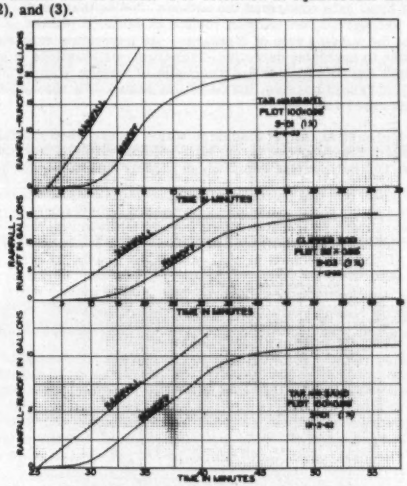

Fig. 1--Typical tests of plane-surface floor

$$\delta_a = (0.0136\ell^{0.318}\sigma^{0.535}/S_0^{0.4615}) \quad \text{for sand} \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

$$\delta_a = (0.0257\ell^{0.384}\sigma^{0.351}/S_0^{0.367}) \quad \text{for gravel} \quad \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

$$\delta_a = (0.078\ell^{0.322}\sigma^{0.325}/S_0^{0.281}) \quad \text{for sod} \quad \ldots\ldots\ldots\ldots\ldots\ldots (3)$$

in which δ_a = average depth of detention at equilibrium in inches, ℓ = length along path of flow in feet, σ = rate of net rainfall in inches per hour, and S_0 = slope of plane surface in per cent. Reduced to terms used by the authors [it is assumed from a check of Figures 1 to 4 with equation (7) that the absolute slope in feet per foot is used], these equations become

$$d_a = (0.000135\, L^{0.318}\, p^{0.535} / s^{0.4615}) \quad \ldots\ldots\ldots\ldots\ldots\ldots (1a)$$

$$d_a = (0.000395\, L^{0.384}\, p^{0.351} / s^{0.367}) \quad \ldots\ldots\ldots\ldots\ldots\ldots (2a)$$

$$d_a = (0.001781\, L^{0.322}\, p^{0.325} / s^{0.281}) \quad \ldots\ldots\ldots\ldots\ldots\ldots (3a)$$

Using the relation that d_a is approximately 0.75 (1/m) of the depth at the end of the plot, equation (7) can be rewritten as in (7a).

$$d_a = (0.000273\, L^{0.3}\, p^{0.54} / s^{0.3}) \quad \ldots\ldots\ldots\ldots\ldots\ldots (7a)$$

Equations (7a) and (1a) differ in the coefficients and in the exponents of s and S; the authors' plot surface may have differed from the surface of sand sprinkled on hot tar used in the local tests; however, the data for equation (1a) were erratic because of the difficulty of maintaining a true plane with so smooth a surface, and can be expressed substantially by equation (7a). It is interesting to note that if equation (7a) is transformed into terms of equation (1), the coefficient becomes 0.01314.

There is no basis for comparison for equations (2a) and (3a); however, the data for these equations were more uniform in agreement and the equations appear to be correct for the types of surfaces tested.

Further check of local data confirmed the authors' finding that, on the rising and on the recession-sides of the hydrograph, the varying volume of detention plotted as a straight line on logarithmic paper against the varying rate of discharge. An interesting extension of these phenomena was found by the writer in analyzing detention-discharge-rate relations in storm-drain gagings, of surface-runoff where the detention is the composite of surface, gutter, and conduit detentions [2]. In this case, on the recession-side, the detention plotted as a straight line on rectangular coordinate paper against rate of discharge.

The momentary increase in rate of discharge which occurs when rainfall ceases raises a question as to what effect the impact of large, high-velocity drops of very intense rainfall has on detention. The writer has noticed that detention on smooth sidewalks during such rainfall seems

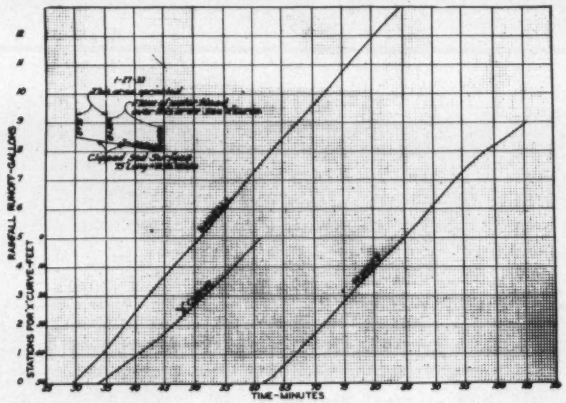

Fig. 2--Typical runoff across unsprinkled area

deeper than would be inferred from the tests.

In studying the hydraulic characteristics of sheet-flow on sod, data were taken for uniform flow by sprinkling a section of the surface a measured distance upstream from the outlet (see Fig. 2). The behavior of the runoff was first to build up full detention and then to flow along the unsprinkled surface as a miniature bore at practically a uniform velocity. The "X"-curve represents the time of arrival of the head of the bore at specified stations. No similar tests were made for gravel or sand. The writer has not analyzed the data fully but believes it may have some significance in the building up of detention on rough surfaces.

In extending the investigations to the rougher paved surfaces and to sod, it seems desirable that such surfaces be given a coefficient of rugosity similar to the coefficient "n" used in channel and conduit hydraulic computation. In the case of sod, it seems logical to expect a wide variation in hydraulic phenomena between the springy turf of carefully cultivated lawns and the hard sparse lawn often encountered in residential districts. The development and description of such a scale of rugosity will increase the value of the results of the investigation to engineers.

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A SUMMARY OF SOIL-MOISTURE DATA USEFUL IN SOIL- AND WATER-CONSERVATION INVESTIGATIONS

F. R. Dreibelbis

This report summarizes some of the more important results obtained in soil-moisture investigations which were first begun at this station--the North Appalachian Experimental Watershed (Coshocton, Ohio)--in 1937 and which were carried on as a help in the evaluation of land-use effects on soil- and water-conservation and on floods. The importance that the soil-profile bears as a medium of water-storage capacity has long been recognized particularly in irrigation-practices. In the humid region where soil-moisture is often a limiting factor in crop-growth, the importance of the soil-profile is being recognized more fully both as a factor in providing moisture for the growth of crops as well as for its effects on stream-flow in time of floods. In a recent study HURSH and FLETCHER [see 6 of "References" at end of paper] have concluded that the analogy of the storage-functions of the soil-profile to storage in artificial reservoirs is entirely justifiable. The use of such an analogy was stated to be advantageous in evaluating land-use effects upon stream-behavior in terms of area inches of storage and runoff.

A knowledge of the changes in the amount of water held in the profile, in its distribution in various horizons of the profile, and in the available storage-capacity of the soil should prove useful both from the agronomic viewpoint as well as that of flood-control. The hydrologic installations at the North Appalachian Experimental Watershed afford a good opportunity of correlating soil-moisture data with other hydrologic measurements such as precipitation, runoff, and percolation. Most of the data presented cover the three-year period 1940-42; in the first of these years a precipitation several inches above the 40-year average (for Coshocton, Ohio) was recorded while in the last two years the precipitation was several inches below this average. The data for each of the three years should give a general idea of the soil-water relationships on woodland, pasture, and cultivated soils and their influence on soil- and water-conservation. No attempt is made to review the literature in such a broad field of investigation. The Hydraulic Data Bulletins [9, 10], as well as a number of other papers [3, 4, 5, 7] from this station have presented data bearing on this subject.

Experimental plan and procedure

Soil-moisture measurements were made to a 40-inch depth at four watersheds at various times during the years 1940-42. The watersheds studied were approximately two acres in area and represented woodland (No. 131), pasture (No. 102), cultivated Muskingum silt-loam (No. 109), and cultivated Keene silt-loam (No. 123). The moisture was determined at soil-depths of 0 to 7, 7 to 14, 22 to 28, and 32 to 40 inches. From volume-weight data previously obtained in four seasons of the year representing these respective depths, the soil-moisture was converted to percentage by volume from which the inches of water in the profile could be calculated. The soil-moisture was determined gravimetrically using the KING tube-sampler and the soil-auger for obtaining the samples. Eight samples were taken just outside each watershed at various points along the perimeter that were most representative of the area, except in the woodland where 18 such samples were obtained. Data on the variability of all these sampling-locations were previously given [3]. Although other methods of determining soil-moisture are in use, no other reliable method for obtaining soil-moisture data at all ranges of moisture-content was available at the time this study was initiated. A more detailed description of the watersheds and the methods used were given in previous publications [3, 4, 5, 9].

Precipitation was measured by recording and standard rain-gages located at a number of points in the experimental area. Water-level recorders for measuring water-depths in precalibrated flumes were used to obtain data on quantities and rates of runoff from these drainage-areas.

Results and discussion

The distribution of soil-moisture in the profile 0 to 40 inches from four watersheds expressed in percentage by volume is illustrated in Figure 1 for approximately monthly intervals during the year 1941. In general the woodland-watershed retained the least water and the cultivated Keene silt-

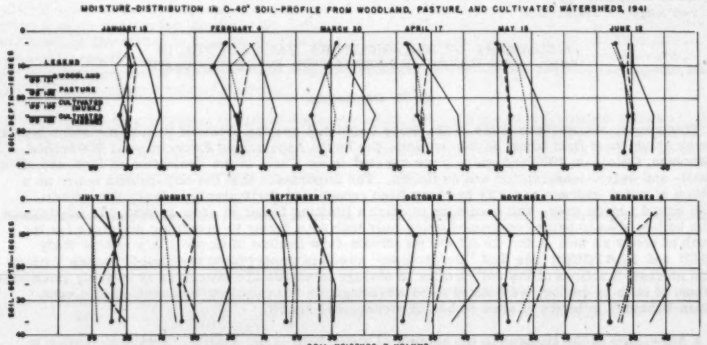

Fig. 1--Comparative moisture-distribution in soil-profiles from woodland, pasture, and two cultivated watersheds at approximately monthly intervals in 1941 (points plotted at center of profile-section samples, that is, moisture in section 32-40 inches is plotted at 36 inches

loam the most. The other watersheds are intermediate between these extremes. During the winter and early spring the soil-moisture content was built up in all four watersheds reaching the maximum in March. In April when appreciable evapotranspiration occurred the removal of water from the upper part of the profile was evident in all four soils. The minimum quantity of soil-moisture throughout the profile was found in August and September. From October through November and December the volume of soil-water stored so increased that the level of moisture which prevailed in early spring was nearly restored. These results, of course, apply only to the particular dates the soils were sampled. (Soil-moisture for days or periods other than for those sampled have not been determined.) Obviously conditions of weather, including rainfall, temperature, humidity, and wind-velocity affect these values. The data do offer a picture of moisture-distribution in the soil-

profile for average conditions prevailing in this region. The effect of soil-type is revealed by a comparison of the two cultivated watersheds (Nos. 109 and 123). Land-use differences can be fairly well compared by the three watersheds (Nos. 102, 109, and 131) where the soils belong to the Muskingum series.

To show the difference in moisture-distribution by years the data from the pastured watershed were plotted for three successive years ending in 1942 and appear in Figure 2. Since the land-use

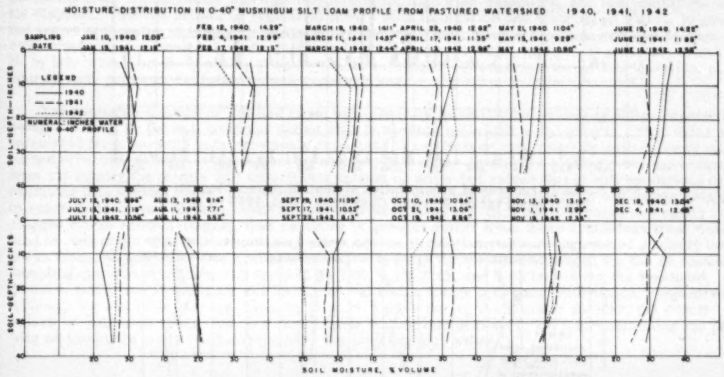

Fig. 2--Comparative moisture-distribution in soil-profiles from pasture watershed at approximately monthly intervals for three successive years ending in 1942 (plotted as in Fig. 1)

was the same for all three years the differences are due largely to the peculiar conditions of weather prevailing for the particular year involved. The amount of water in the profile 0 to 40 inches expressed in inches is also given for each sampling date. The maximum value (14.57 inches in the profile) was obtained in March, 1941, while the minimum (5.52 inches) was found in August, 1942. The distribution of moisture throughout the profile was not the same for each year but in general the trends were similar. Daily precipitation-records for the years 1940-42 appear in Figure 3.

A knowledge of the distribution of soil-moisture prior to and following a storm is often very desirable for hydrologists and engineers to assist them in an evaluation of precipitation-disposal. It is not easy to obtain such records because of the difficulty in deciding just when to sample the soils preceding a storm. In June, 1943, however, such records were obtained for four watersheds when the soil-moisture distribution was determined just prior to a storm which began the afternoon of June 15. Rainfall occurred also on June 16 and 17, and the soil was again sampled on June 18. Precipitation from the entire storm amounted to 1.52 inches. These data appear in Figure 4. In all watersheds the increase in moisture-content in the surface-soil is very evident and extends down to the 25-inch depth in watersheds Nos. 102 and 123, while the increase extends beyond the 36-inch depth in watersheds Nos. 131 and 109. As the runoff was negligible on all watersheds the loss of water during the interim was due to evapotranspiration. In the woodland the soil-texture favored the most rapid percolation and this was partly counteracted by the interception of rainfall by vegetation somewhat delaying infiltration. In the two cultivated watersheds the effect of soil-type appeared, the heavier soil (Keene silt-loam, No. 123) retarding penetration at the depth of the most impermeable layer (24 inches). In this work it is realized that the possible experimental error in the sampling-operation is rather large. The data should be interpreted with this in mind.

The soil-water distribution in the profile 0 to 40 inches showing the minimum soil-water content, the active soil-water, and the available storage-capacity at approximately monthly intervals for a three-year period appears in Figure 5. The minimum soil-water content was determined by selecting the lowest field-moisture content for the six-year period of record and expressing it in inches (shown on Fig. 5 as amount of soil-water permanently held). While it is possible this value

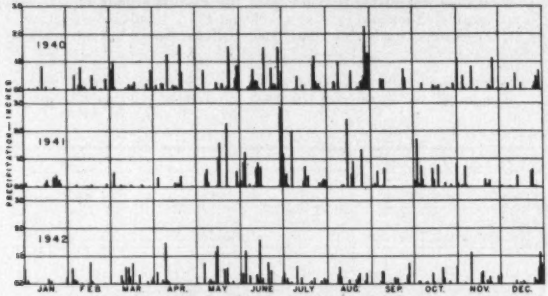

Fig. 3--Daily records of precipitation at central meteorological station, Soil Conservation Service, Coshocton, Ohio, 1940 to 1942

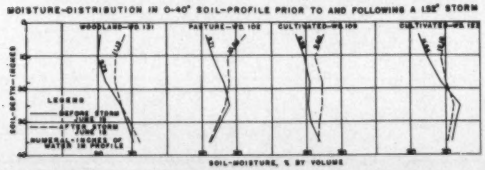

Fig. 4--Moisture-distribution in soil-profiles from woodland, pasture, and two cultivated watersheds prior to and following a storm of 1.52 inches in June, 1943 (points plotted as in Fig. 1)

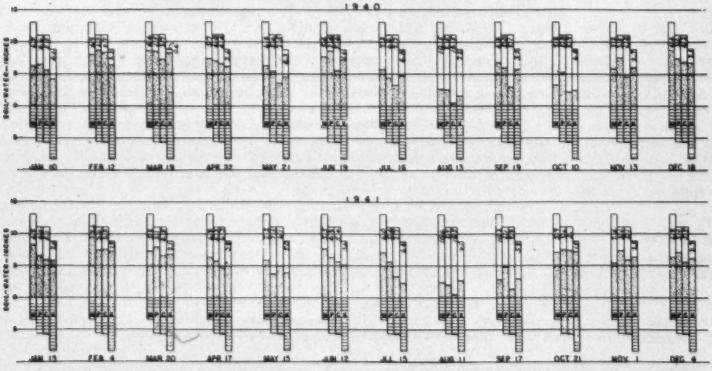

Fig. 5--Accounting of moisture-distribution in soil-profiles from woodland, pasture, and two cultivated watersheds showing amount of soil-water permanently held, active soil-water, and unfilled reservoir-capacity for 34 monthly intervals, 1940 to 1942 (expressed in inches water in zero to 40-inch profile)

may become even lower during a very prolonged dry period it is likely such cases will be very rare and the values submitted will be more useful for the purpose of this study. The magnitude of the minimum soil-water content at the various locations is a reflection of the soil-texture, the lightest textured soil showing the least amount held and the heaviest soil the most. The volume of water held exceeding this amount will be classified as active soil-water [4] which is available for disposal through percolation, evapotranspiration, or seepage and which also may influence surface-runoff; it is governed to a great extent by meteorological conditions since precipitation and condensation favor its accretion and high temperatures, high wind-velocities, and low humidities favor its disposal. Profuse growth of vegetation favors both infiltration and disposal of water. In general the active soil-water is lowest in late summer and early fall, after it has been reduced by high evapotranspiration rates during the summer [4], and begins to build up and increases in volume until by late winter or early spring it again reaches its peak. Unusual storms of long duration, of course, may prove an exception to this general trend.

The available storage or unfilled reservoir-capacity indicates the volume of water capable of being absorbed by the soil over and above what is already contained in the profile. This value was calculated from porosity data previously reported [5] and further confirmed by soil-cores of undisturbed structure brought to saturation by standing in a water-bath. The available storage-capacity does not signify the profile will absorb this amount of water but rather that it will be capable of receiving this amount should the proper conditions of infiltration permit. It is not always related to runoff because the surface-conditions in cultivated soils are such that the pores are easily clogged due to rainfall-impact, thus resulting in greater runoff from these areas than from woodland or sod-crops where the cushioning effect of this vegetation reduces impact and protects the pores from clogging [2]. The available storage-capacity values were averaged for the 34 monthly sampling-periods presented and found to be 7.01, 5.11, 6.15, and 3.68 inches for the woodland, pasture, cultivated Muskingum silt loam, and cultivated Keene silt-loam watersheds, respectively. Although the available storage-capacity is much higher during the summer months, the runoff-values in cultivated areas, too, are often higher during this period [9, 10] thus confirming the necessity of employing conservation-practices for trapping this water.

Table 1--A summary of soil moisture data representing the 0 to 40-inch profile

Watershed No.	Land-use	Soil-type	Calculated maximum possible water-storage	Minimum field-moisture found	Difference possible accretion	Maximum active soil-water found	Hygroscopic moisture[a]
			in	in	in	in	in
131	Woodland	Muskingum loam	16.52	3.41	13.11	9.60	1.41
102	Pasture	Muskingum silt-loam	16.61	5.52	11.09	9.05	1.75
109	Cultivated	Muskingum silt-loam	16.76	5.71	11.05	8.49	2.60
123	Cultivated	Keene silt-loam	17.10	8.30	8.80	8.38	4.60

[a] Determined over 3.3 per cent of H_2SO_4.

A summary of soil-moisture-data representing the profile 0 to 40 inches is presented in Table 1. The depth of 40 inches is arbitrary and obviously where the soil-reservoir exceeds this depth the storage-capacity is likely to be greater and where less than 40 inches, to be lower. The latter situation is not uncommon in the woodland. The calculated maximum possible water-storage (the amount of water the soil theoretically would hold if all the pore-space were occupied by water) for the 40-inch profile ranges from 16.52 inches in the woodland to 17.10 inches on the cultivated Keene silt-loam. These values are similar to those of MIDDLETON [8], who found 16.2 inches for the 36-inch profile of Muskingum silt-loam sampled at Zanesville, Ohio. The minimum soil-water content found during the period 1937-43 (Fig. 5) ranges from 3.41 inches in the woodland to 8.30 inches in the cultivated Keene silt-loam. The differences, (Table 1) which represent the possible accretion to the watersheds, when at the minimum soil-moisture content, range from 8.80 inches on the Keene silt-loam to 13.11 inches in the woodland.

The soil-moisture data presented should prove especially helpful in soil-hydrology. These values emphasize the fact that the soil-profile can function as a storage-capacity medium. Data on the

maximum active soil-water obtained indicate that the soil-profile during the three-year period could accumulate or release an amount of water-equivalent to 8.38 inches on the Keene silt-loam cultivated watershed and 9.60 inches on woodland--the other areas being intermediate between these extremes. The amount of water the profile may accumulate will depend on the amount of soil-water already present. Obviously, in late winter or early spring when the available storage-capacity is rather low no great amount may be accumulated, but if storms of great intensity prevail at such time there is likely to be much runoff tending to produce floods. (Floods sometimes occur at this time of year due to high runoff from rapidly melting snow and thawing and also from prolonged rainfall at rather low intensities; subsurface-flow also may be increased at such times so that floods may result in the larger rivers if not on the lesser streams.) Fortunately, at this time of year most storms are of low intensity in this region [1] and severe runoff is not so likely to occur except in the above-mentioned cases (see also Fig. 3). During the summer months when, ordinarily, the available storage-capacity is high, the profile will be able to hold a relatively large amount of water. At this season, however, many storms are of such high intensity that not all the water will infiltrate into the soil and much is likely to run off even though the profile would be capable of holding it. This emphasizes the need of conservation-practices in this region where much of the topography often favors high runoff and where conservation practices generally have proved very effective.

The amount of water in the profile in excess of the field-capacity is usually held but a relatively short time. It is, however, very important from the viewpoint of flood-control because much of this water is likely to contribute to storm-runoff. Little of this excess water is used by plants and, seemingly, is of little consequence from an agronomic point of view unless the excessive moisture retards plant-growth due to lack of aeration.

A knowledge of the available storage-capacity is useful in predicting what amount of water the soil will be able to hold under the conditions represented by the woodland, pasture, and cultivated watersheds studied. It serves as a measure of the ability of the soil to store water at various times during the year. While the peculiar meteorological conditions prevailing at the time would influence these values, the general trend shows that the profile will be able to hold more water during the late summer and early fall than in late winter and early spring. The average of 34 monthly values indicates the comparatively greater storage-opportunity in the woodland than in the other land-use areas studied. The influence of soil-type in this respect is revealed by a comparison of the data from the two cultivated watersheds where the average storage-opportunity is much greater on the Muskingum silt-loam than on the Keene silt-loam.

In woodland soils biological channels and structural voids occur which not only facilitate soil-water movement but also serve as part of the soil-water reservoir as was pointed out by HURSH and FLETCHER [6]. The measurement of soil-moisture and soil-porosity is more difficult and less accurate where such voids and channels are encountered. The soil-moisture values given in this paper, therefore, are likely to be least accurate for the woodland areas where large roots, and numerous biological channels provide pores of non-capillary size that enhance the water-storage opportunity of the soil.

Previous data on soil-porosity [5] have indicated the percentage saturation (by volume) at pF 1.6 of the same soil-profiles that are studied in this paper. (The pF-scale is used to express soil-moisture on an energy-basis. pF is defined as the logarithm of the height in cm of a liquid column that is necessary to produce the desired suction at which the remaining water is held in the soil. pF 1.6 (40-cm tension) represents the approximate dividing line between capillary and non-capillary pores.) If these values are converted to inches of water for the 40-inch profile and subtracted from the inches of water in the profile at saturation (see Table 1) the differences range from 3.5 to 4.3 inches for the Muskingum profiles. Although the entire profile seldom becomes saturated, these differences indicate that under certain conditions soil-water is likely to make an appreciable contribution to storm-runoff. During the summer and fall months percolation through the profile is generally very low and frequently the water of infiltration is entirely absorbed by the soil which can store a relatively large amount of water during these periods before percolation begins. Soils high in clay and colloids swell when wet and the pores become smaller so that infiltration is reduced under such conditions. The Muskingum profiles, however, have a low clay-content throughout the profile [3] and generally have as high infiltration-rates when wet as when dry. The presence of an impermeable layer in the Keene silt-loam retards percolation which also may reduce the effective storage-capacity, at least for the storage of potential flood-waters.

The conception that the soil-profile may function as a storage-reservoir is illustrated by the data presented. Such knowledge should facilitate the forecasting of storm-runoff and the base-flow

of streams and should serve as a basis in comparing the effects of different land-use practices on soil- and water-conservation.

Summary and conclusions

Data on the moisture-content of soil-profiles to a 40-inch depth were presented for woodland, pasture, and two cultivated watersheds for the period 1940-42. The purpose of collecting these data was to furnish one of the several bases for the evaluation of land-use effects on soil- and water-conservation and on floods. The comparative distribution of moisture by depth in the profile was given for these soils at monthly intervals for the year 1941. Similar data for the pasture watershed were given for three successive years ending in 1942 expressed both on a basis of percentage by volume and in inches of water in the profile. Additional data were presented for these soils showing the minimum soil-water content, the active soil-water, and the available storage-capacity, all expressed in terms of inches of water in the profile 0 to 40 inches. Data on the distribution of soil-moisture in four profiles prior to and following a rainstorm of 1.52 inches were also given.

The data indicate the relative value of the soils on these different land-use areas as a storage-capacity medium and should be useful both from an agronomic viewpoint as well as that of flood-control. They emphasize the conception that the soil-profile may function as a storage-reservoir.

The results also indicate that the possible accretion to the soil-profile 0 to 40 inches amounts to 13.11, 11.09, 11.05, and 8.80 inches for the woodland, pasture, cultivated Muskingum silt-loam, and cultivated Keene silt-loam, respectively. The maximum active soil-water found for these same areas was 9.60, 9.05, 8.49, and 8.38 inches, respectively.

The available storage-capacity for the summer months is generally very high and indicates that the profile will be able to hold much additional moisture if it infiltrates into the soil. This emphasizes the need for conservation-practices in this region where storms of high intensity during these months are often likely to occur, and where much of the topography favors high runoff. The average of 34 monthly values of the available storage-capacity of these soils was 7.01, 5.11, 6.15, and 3.68 inches for the woodland, pasture, and two cultivated watersheds, respectively.

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THE HYDROLOGIC BEHAVIOR OF AGRICULTURAL WATERSHEDS

Waldo E. Smith

During the past decade there has been much discussion, pro and con, with regard to the effects of agricultural operations upon the amount and regimen of runoff from watersheds. The problem becomes highly involved on large watersheds, because they are made up of various complexes of soil, cover, topography, and other edaphic features. Some of these features are subject to rapid or seasonal change and others are relatively unchanging. On plots it has been established that great changes can be effected, and many data are available that show qualitative and quantitative differences in volumes of runoff. Intermediate between the plot and the large heterogeneous watershed is the small single-cover watershed. For such areas data have been presented indicating trends toward change, but little has been presented that provides a measure of this change. We need to know what change in hydrologic behavior will result from the changing of a given set of circumstances. It was the objective in this study to present a means of evaluation. While this objective has not been fully attained, perhaps enough progress has been made to warrant a reporting at this time, in the hope that it may stimulate others to pursue a similar course to a more definite end.

As a basis for this study, the author has used data gathered at the North Appalachian Experimental Watershed, Coshocton, Ohio, for small single-cover watersheds 109, 110, 113, 115, 123, and 192 in the years 1940 [see 1 of "References" at end of paper] and 1942 [2]. These watersheds were selected because they were the only ones for which the available records were in good order for both of the storms selected for study. In June, 1940, all of these watersheds were in wheat under farming practices prevailing in that locality, but in 1942 they were in diverse covers, as shown in Table 1. This table also shows other characteristics of these watersheds.

Table 1--Characteristics of watersheds and data on storms

Watershed No.	Area	Average slope	Predominant[a] soil-type	June 10, 1940				June 14, 1942			
				Cover		Rainfall	Runoff	Cover		Rainfall	Runoff
				Type[b]	Height			Type[b]	Height		
	ac	pct			in	in	in		in	in	in
109	1.69	12.7	MSL	PW	25	.87	.426	IW	38	1.60	.002
110	1.27	13.0	KSL	PW	..	.71	.270	PC	10	1.66	.212
113	1.45	9.3	CSL	PW	21	.62	.271	PM_2	13	1.54	.041
115	1.61	6.6	MSL	PW	22	.78	.264	PW	38	1.49	.012
123	1.37	5.8	KSL	PW	24	.78	.066	IW	41	1.49	.023
192	7.86	15.8	MSL	PW	23	.82	.260	PC	9	1.49	.252

[a]Descriptions of soils of the various watersheds are found in Hydrologic Bull. 1 and 4 [North Appalachian Experimental Watershed, Coshocton, Ohio, 1939 and 1940, respectively], in tables giving the runoff from the several watersheds. MSL is Muskingum silt-loam, which is a residual upland, relatively shallow soil derived largely from sandstone, and generally the most open-textured of the three soils listed. CSL is Coshocton silt-loam, also a residual upland soil, but derived from sandstone and shale; it is generally somewhat less open-textured than Muskingum silt-loam. KSL is Keene silt-loam, also a residual upland soil, but is derived chiefly from shale; it is generally the most clayey soil of these three.

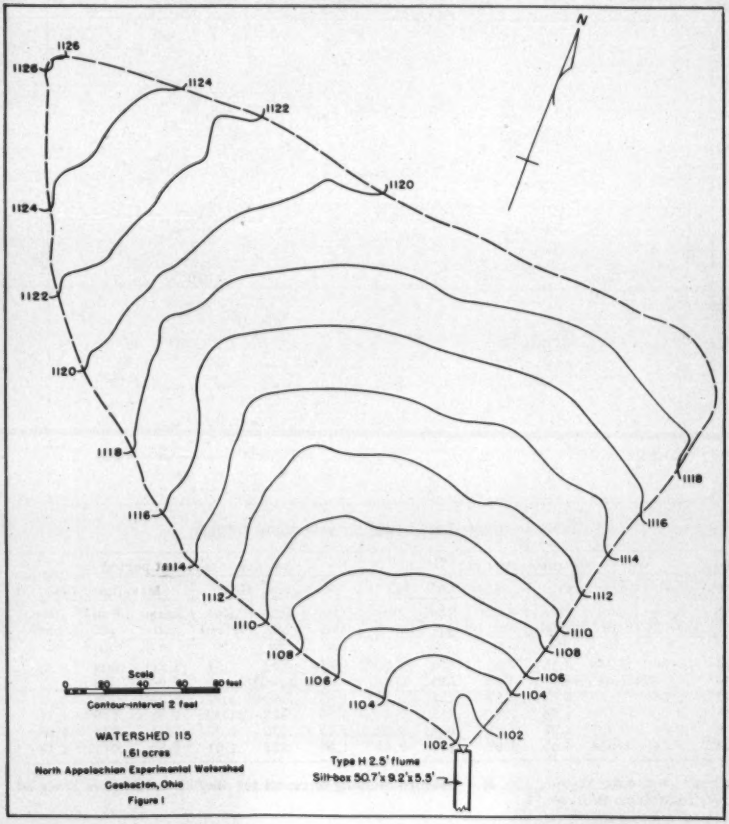
[b]PW stands for wheat raised by the farming practices prevailing on the farms in that region. IW stands for wheat raised by improved farming practices, usually contour-cultivation with lime and fertilizer added in addition to amounts generally used in the area. PC stands for corn raised according to the local farming practices, usually in rows or hills. PM_2 is second-year meadow under prevailing farming practices.

Figures 1 and 2 are contour-maps of watersheds 115 and 123, which, though somewhat flatter than the others, are rather typical of these small watersheds.

In the early afternoon of June 10, 1940, a series of rains totaling somewhat less than an inch occurred that resulted in substantial runoff from all six of the watersheds (see Table 1). Two years later, in the early morning of June 14, 1942, a series of rains totaling about one and a half inches occurred at intensities comparable to those of the storm of 1940. All watersheds, including those

in wheat under prevailing practices, produced less runoff than in the storm of 1940, as shown in Table 1.

Antecedent conditions appeared to be quite similar, as suggested by the graphs of temperature and precipitation in Figure 3. For the antecedent ten-day periods the temperature in 1942 averaged somewhat higher, though precipitation was quite similar. For the antecedent 44 days, Table 2 shows that there was more precipitation, but less runoff, in 1942 than in 1940. Yet, soil-moisture observations of Table 3, determined by methods described by DREIBELBIS and POST [3], indicate about equal amounts of soil-moisture in a 40-inch column of soil on June 5, 1940 (five days prior to the storm under study) and June 3, 1942 (11 days prior to the storm under study, within which 11-day period a rain of nearly an inch fell on June 4). After each storm, the moisture-content was again almost identical for a given watershed. No attempt has been made to reconcile differences further.



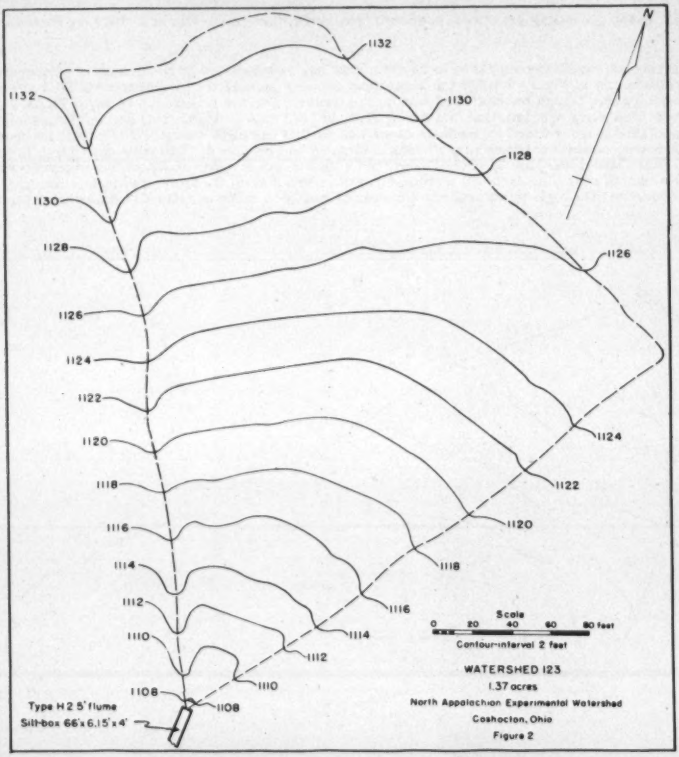


Figure 2

Table 2--Rainfall and runoff for antecedent periods

Water-shed No.	44-day antecedent period						14-day antecedent period					
	May-June, 1940			May-June, 1942			May-June, 1940			May-June, 1942		
	Rain-fall[a]	Run-off	Re-tained	Rain-fall	Run-off	Re-tained	Rain-fall	Run-off	Re-tained	Rain-fall	Run-off	Re-tained
	in	in	in	in	in	in	in	in	in	in	in	in
109	5.04	0.936	4.10	7.50	.004	7.50	1.83	.285	1.54	2.33	.004	2.33
110	Not available			6.57	.575	6.00	Not available			1.90	.093	1.81
113	5.04	1.16+[b]	3.88-	6.57	.133	5.24	1.83	.101+[b]	1.73-	1.90	.092	1.81
115	5.04	1.10	3.94	7.61	.153	7.46	1.83	.427	1.40	2.86	.119	2.74
123	5.04	0.309	4.73	7.61	.004	7.61	1.83	.025	1.80	2.86	.003	2.86
192	5.04	0.569	4.47	5.97	.277	5.69	1.83	.223	1.61	1.39	.071	1.32

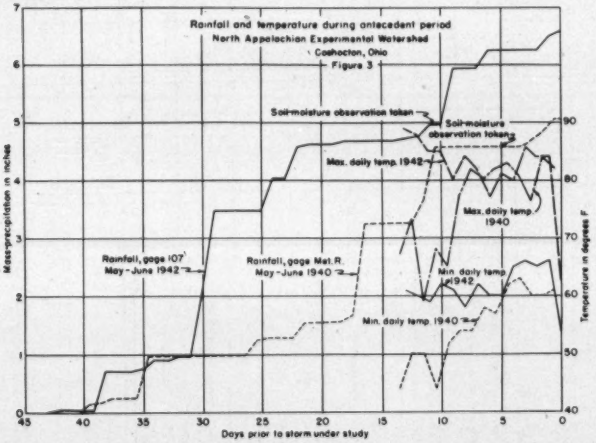
[a]Rainfall record for station, Met. R. [b]Record missing of runoff for May 29 and 30 [see Table 30, p. 193, Hydrologic Bull. No. 4].

Table 3--Soil-moisture and rainfall, watersheds 109 and 123

Item	Watershed	
	109	123
	in	in
Soil-moisture, June 5, 1940	11[a]	14[a]
Soil-moisture, June 12, 1940	13[a]	15[a]
Gain in moisture	2	1
Rainfall, June 5 to 12	2.00	1.87
Runoff	0.588	0.080
Retained	1.41	1.79
Soil-moisture, June 3, 1942	10.49[a]	14.13[a]
Soil-moisture, June 15, 1942	12.8[a]	14.97[a]
Gain in moisture	2.31	0.84
Rainfall, June 3 to 15	3.49	3.57
Runoff	0.006	0.026
Water retained	3.48	3.54

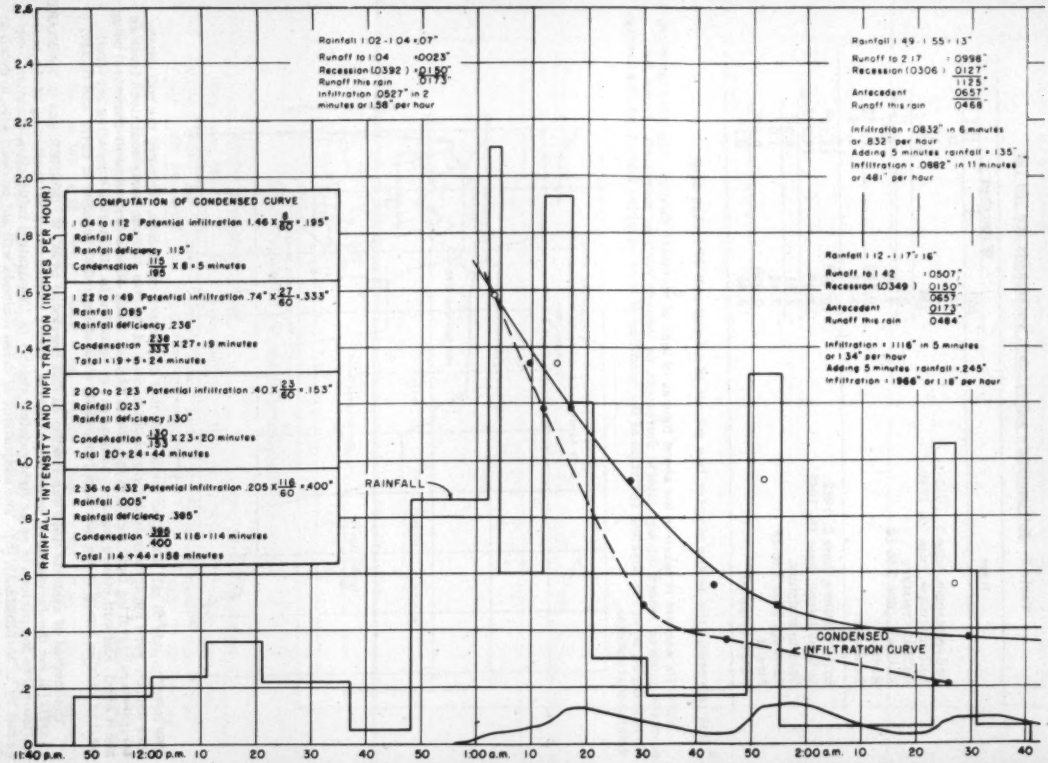
[a] This represents the depths of water in a column of natural soil 40 inches deep.

Note: No account is taken in the above figures of loss of moisture through evapotranspiration, or of the gains or losses through lateral movement, or through vertical movement across the 40-inch depth, or of the possible deviation of the condition of core-samples taken from the average watershed-condition.



The intent is only to call attention to the fact that antecedent conditions, including the soil-moisture aspect, were apparently nearly equal in the case of the two storms, some conditions (such as temperature) favoring light runoff in the storm of June, 1942, others (such as soil-moisture) being about equal, and still others (such as amount of precipitation in the storm) suggesting the likelihood of heavier runoff in the storm of June, 1942, without regard to changes in cover and tillage.

The method of analysis used was similar to that suggested by W. W. HORNER and C. LEONARD LLOYD [4] for the derivation of infiltration-curves, with a condensation or shortening of the infiltration-curve for periods of no or light rainfall similar to "equivalent infiltration-duration" suggested by L. K. SHERMAN [5]. The adaptations of these methods will not be dealt with in detail in this paper, but computations are shown for the analysis of one hydrograph in Figure 4. A curve of


RAINFALL INTENSITY AND INFILTRATION (INCHES PER HOUR)
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
.8
.6
.4
.2
0
11:40 p.m. 50 12:00 p.m. 10 20 30 40 50 1:00 a.m. 10 20 30 40 50 2:00 a.m. 10 20 30 40
Rainfall 1.02 - 1.04 = .07"
Runoff to 1.04 = .0023"
Recession (.0392) = .0150"
Runoff this rain = .0173"
Infiltration .0527" in 2 minutes or 1.58" per hour
Rainfall 1.49 - 1.55 = .13"
Runoff to 2.17 = .0998"
Recession (.0306) = .0127"
1125"
Antecedent .0657"
Runoff this rain .0468"
Infiltration = .0832" in 6 minutes or .832" per hour
Adding 5 minutes rainfall = .135"
Infiltration = .0882" in 11 minutes or 481" per hour
COMPUTATION OF CONDENSED CURVE
1.04 to 1.12 Potential infiltration 1.46 X 8/60 = .195"
Rainfall .08"
Rainfall deficiency .115"
Condensation .115/.195 X 8 = 5 minutes
1.22 to 1.49 Potential infiltration .74" X 27/60 = .333"
Rainfall .095"
Rainfall deficiency .238"
Condensation .238/.333 X 27 = 19 minutes
Total = 19 + 5 = 24 minutes
2.00 to 2.23 Potential infiltration .40 X 23/60 = .153"
Rainfall .023"
Rainfall deficiency .130"
Condensation .130/.153 X 23 = 20 minutes
Total 20 + 24 = 44 minutes
2.36 to 4.32 Potential infiltration .205 X 116/60 = .400"
Rainfall .005"
Rainfall deficiency .395"
Condensation .395/.400 X 116 = 114 minutes
Total 114 + 44 = 158 minutes
Rainfall 1.12 - 1.17 = .16"
Runoff to 1.42 = .0507"
Recession (.0349) = .0150"
.0657"
Antecedent .0173"
Runoff this rain .0484"
Infiltration = .1116" in 5 minutes or 1.34" per hour
Adding 5 minutes rainfall = .245"
Infiltration = .1966" or 1.18" per hour
RAINFALL
CONDENSED INFILTRATION CURVE

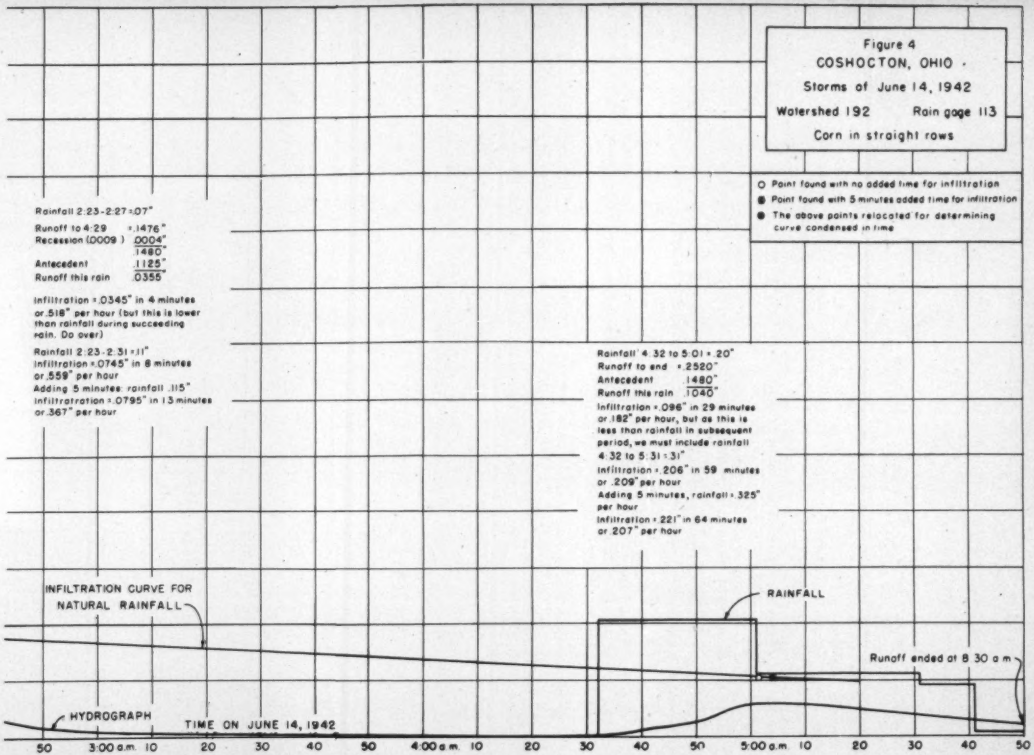
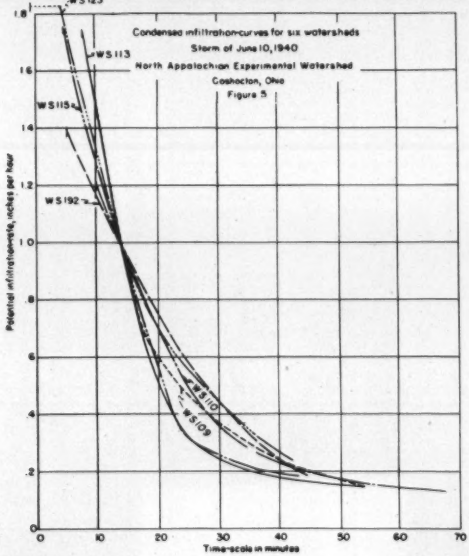


Figure 4
COSHOCTON, OHIO
Storms of June 14, 1942
Watershed 192 Rain gage 113
Corn in straight rows
○ Point found with no added time for infiltration
● Point found with 5 minutes added time for infiltration
● The above points relocated for determining curve condensed in time
Rainfall 2:23-2:27=.07"
Runoff to 4:29 =.1476"
Recession (D009) .0004"
.1480"
Antecedent .1125"
Runoff this rain .0355"
Infiltration =.0345" in 4 minutes or .518" per hour (but this is lower than rainfall during succeeding rain. Do over)
Rainfall 2:23-2:31=.11"
Infiltration =.0745" in 8 minutes or .559" per hour
Adding 5 minutes rainfall .115"
Infiltration =.0795" in 13 minutes or .367" per hour
Rainfall 4:32 to 5:01 = .20"
Runoff to end =.2520"
Antecedent .1480"
Runoff this rain .1040"
Infiltration =.096" in 29 minutes or .182" per hour, but as this is less than rainfall in subsequent period, we must include rainfall 4:32 to 5:31=.31"
Infiltration =.206" in 59 minutes or .209" per hour
Adding 5 minutes, rainfall =.325" per hour
Infiltration =.221" in 64 minutes or .207" per hour
INFILTRATION CURVE FOR NATURAL RAINFALL
RAINFALL
Runoff ended at 8 30 a m
HYDROGRAPH
TIME ON JUNE 14, 1942
50 3:00 a.m. 10 20 30 40 50 4:00 a.m. 10 20 30 40 50 5:00 a.m. 10 20 30 40 50

infiltration is computed and drawn for the natural sequence of rain by the HORNER method, after which an equivalent or condensed time is found for periods of non-runoff such that with rain occurring in periods at the potential infiltration-rate, the condensed time is just sufficient for the rain that fell to have infiltrated. The mass-infiltration for the interval occurs at what R. E. HORTON has called "infiltration-capacity"[6].

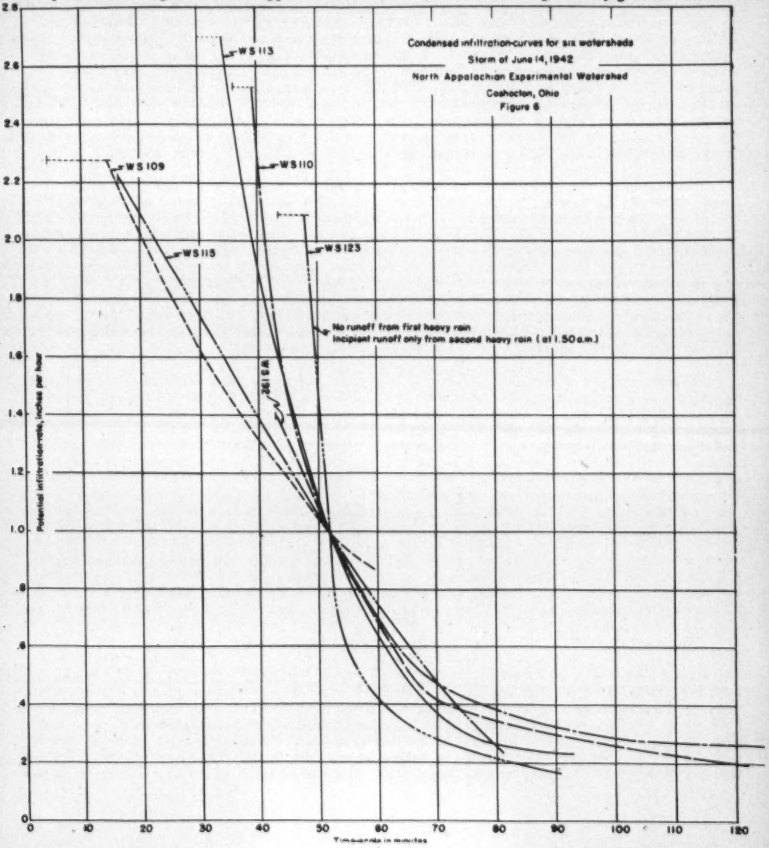
With regard to the three types of points shown in Figure 4, an open circle represents the average infiltration-rate for a given interval, computed for the actual interval of rainfall from the difference of rainfall and runoff. However, if there is substantial runoff, water covers the entire watershed at the moment that rain ceases. The runoff concentrates quite rapidly into rills and is depleted through infiltration after cessation of rainfall. After a few minutes, there is surface-water only in the rills. Finally, after the last rill has drained and a channel carrying intermittent flow is again quite free of surface-water, infiltration on the watershed ceases. The infiltration during the period from end of rainfall to end of runoff may be assumed to occur over the entire surficial area for a short period instead of a decreasing portion of the area for this entire recession-period. After numerous trials, on this and related work regarding these small watersheds, a five-minute period was selected as a satisfactory one to use in lieu of the entire period of recession. A point thus found is plotted as ⊠. If runoff was light, the amount of water on the surface of the watershed might be insufficient to sustain the infiltration for this five-minute period, and thus a true value of average infiltration-rate for the shower or burst of storm would lie somewhere between the rate determined for the rainfall-period alone, and for that period plus five minutes. Adjustment was made in the computations for rainfall during the added five-minute period. If there was substantial runoff, this plotting was given special weight in the drawing of the curve. But if the runoff was light, the open circle was given the greater weight. The solid circles are for the condensed curve and were computed for each of the points with and without added time, giving special weight to the one of the two in each burst or shower that was given special weight in drawing the curve for the natural sequence of rain.

By this method, infiltration-curves were derived for the six watersheds for both storms. The first curve derived, in each case, was for the natural sequence of rains, from which the condensed curves were finally derived. The condensed curves derived for the storm of June 10, 1940, are shown in Figure 5. These were adjusted in time-position to cross the one-inch-per-hour infiltration-



rate at a common point, but, for each curve, the rate at the beginning of runoff is indicated by its left-hand extremity. Digressing a moment, a group of such individual watershed-curves for a common cover-and-soil complex has been used to derive graphically a composite curve to be expanded in turn to natural rain-sequence for use for the determination of the runoff for the same rain on larger mixed-cover watersheds. While beyond the scope of the present paper, this effort was sufficiently successful in its observed-versus-computed runoff to offer encouragement that the method held promise in the analysis of larger, mixed-cover watersheds. Referring again to Figure 5, if one considers the fact that the watersheds are not identical, but vary in size, slope, shape, soil, and density of cover, as well as in rainfall-pattern to some degree, and allows for appreciable error in the observed data on rainfall and runoff, it appears that the agreement between these curves is remarkably close.

The same sorts of curves were derived for the conditions extant during the storm of June, 1942. These condensed curves were again brought together at the one-inch-per-hour infiltration-rate and are reproduced in Figure 6. It is apparent at once that infiltration was generally greater than it was



in the storm of 1940, including that for the watershed planted to wheat under prevailing farm practices, although it appeared, as stated earlier, that antecedent conditions, including soil-moisture, were quite similar to those extant in 1940. Wheat was taller and more lush in 1942 than in 1940. This may be one factor, but unknown variables probably aided in the alteration of the situation.

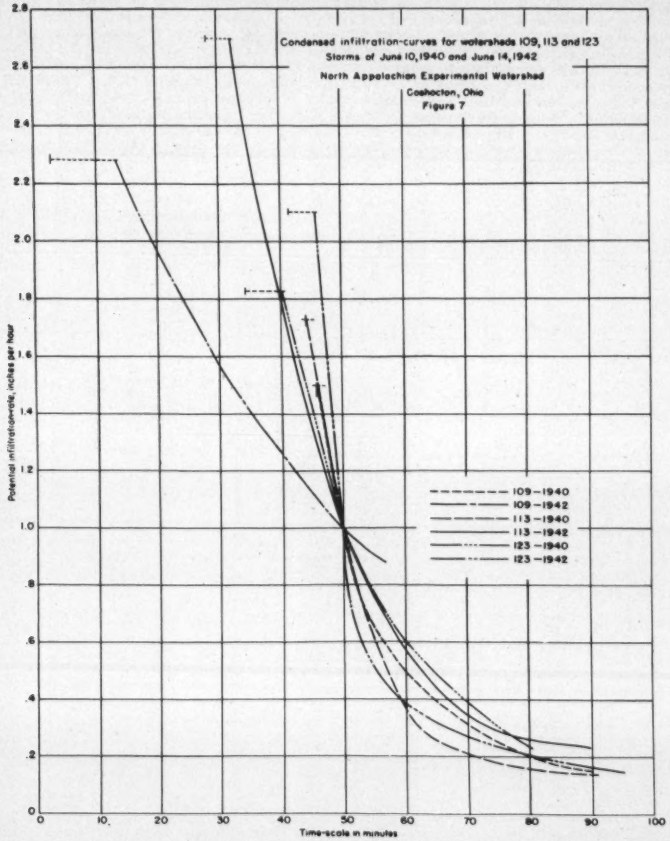
A number of outstanding facts become evident, one being that minimum values in 1942 closely approached those of 1940, though a much greater total of infiltration occurred before these values were reached in 1942. Another outstanding feature is the wide dispersion of the curves in 1942 as compared with 1940, indicating a lack of uniformity in behavior. This might be due in part to the fact that the curves for the storm of 1942 were generally less well defined than those for that of 1940, because runoff was less and may have occurred in some instances only from the more impervious parts of the area rather than the whole area. In some cases runoff was so small that it was deemed to be incipient and the rate of rainfall was taken as the rate of infiltration. Yet the tendency toward dispersion is probably significant.

Watershed 109 produced a great deal of runoff at very high rates in 1940, and may be described as the "worst performer" of the group. In 1942, we find a complete reversal in behavior, and Watershed 109, then in wheat-cover under improved practices, produced the least runoff of the six. On the other hand, Watershed 192, which was average in its delivery of water in 1940, produced, under straight-row corn culture, the greatest runoff in 1942 and perhaps would have delivered greater total flow had it not been cultivated within a week prior to June 14. Watershed 110 likewise was an average producer of runoff in 1940, but in straight-row corn was heaviest, next to Watershed 192 in 1942, and would also probably have produced much more had it not been cultivated on June 13, the day preceding the storm under special study. As shown on Figure 6, the initial rate of infiltration of Watershed 110 in 1942 was second only to that of Watershed 113 in meadow.

The rate of decrease of infiltration-rate is also revealing. Watershed 123, on relatively flat slope, when planted to wheat in improved practices in 1942, retained all of the heaviest burst of storm at the beginning of the sequence of rains and most of all of that in the second intense burst, but finally with recurrence of continuing rain at much lower rates, was unable to hold all of this rainfall, indicating an abrupt drop in the infiltration-rate. This tendency was also shown in 1940, as indicated in Figure 7. Watershed 109, on somewhat steeper slope (slope was perhaps an important factor in rapid drop in infiltration-rate in 1940), was found to yield water much more gradually under the improved practices extant in 1942 than in 1940, but it provided a well-sustained infiltration-rate, though it yielded runoff more promptly than Watershed 123. Watershed 113, on moderate slope, tended to maintain its general characteristics of 1940, though cover had been changed to meadow, and some improvement in infiltration-characteristics was noted.

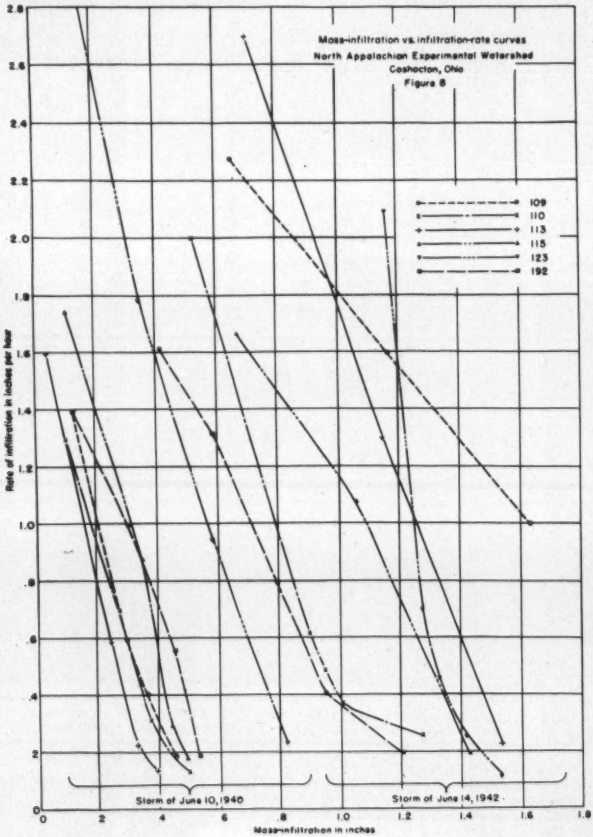
Another means of comparing behavior is the plotting of mass-infiltration up to a given time against its rate at that time. But here what is needed especially is an index of the initial condition so that initial rates may be taken on a comparable basis. Using a method that accepts a given infiltration-rate as a starting point weighs heavily against such watersheds as 123 that infiltrate much water at relatively high rates and rather suddenly decrease to low rates--as one would expect of a relatively impervious watershed covered with spongelike material. A sustained rate, in comparison might be provided by a watershed composed of gradually clogging sieves. Figure 8 shows the curves of mass-infiltration versus infiltration-rate. For reasons already given, not much weight can be given to the positions of the curves in the mass-infiltration position, but their relative positions for a given storm should have some significance. Their slopes vary in the curves for the storm of 1940, but the curves are quite closely grouped. The curves for the storm of 1942 show much more dispersion, and watersheds 192 and 110, in corn, show considerably less infiltration for a given rate than the others. Mass-infiltration was taken from the beginning of the continuous rainfall that generally caused runoff ($23^h\ 47^m$ on June 13, 1942, on Fig. 4) and omitted intermittent light rain that may have amounted to a few hundredths preceding the main storm by a few hours.

Watersheds that behave as Watershed 123, that is, those that admit water at a rate in excess of the ability of the lower horizons to transmit it, are unlikely to have their ultimate minimum infiltration-rates increased by virtue of cover-conditions. For intense, brief storms, such as occur in the Ohio Valley during the summer, the ability to infiltrate at high rates is a decided advantage, not only from the viewpoint of the control of runoff but also with regard to moisture-supply for plant-growth. But on such watersheds, if, by virtue of improved conditions on the surface and in the plow-layer, it is possible to increase the maximum water-holding capacity--say one inch of depth of water--then this will likewise be helpful at any time in the withholding of runoff to the extent that it has not been filled by antecedent rain. The type of watershed whose surface acts like a



clogging sieve under continuing rainfall until the surface is almost sealed through puddling, is usually a watershed with scant cover or with cover such as corn that does not protect the surface against the impact of the rain. Watersheds with good cover, especially if supported by contour-cultivation to decrease opportunities for rapid rilling, usually belong in the former class. There is, also, another type of behavior, namely, a soil-profile with surface and cover such that infiltration does not decrease appreciably with continuing rainfall, such as one finds in open-textured, fragmental, or sandy soils. In such circumstances, either the increments to the ground-water are rapid, or more likely, extensive subsurface flow occurs so that analyses of infiltration afford no useful results. The retentive capacity of the open-textured profile in inches of depth of water is an especially important factor in such circumstances.

Conclusions--While there is a degree of quantitative measurement of the effect of land-use in the methods outlined in this paper, further studies are necessary to reduce such a technique to provide definite quantitative values. Among the essentials yet required for success are : (1) An index of antecedent conditions from which measurements of time may be taken for the infiltration-curves and as a base from which to measure mass-infiltration--various measures have been devised and used with varying degrees of success , for example, by HORNER [7] and SHERMAN [8]; (2) quantitative measurements of soil-moisture in the profile just prior to, and just following, storms of the type under analysis, with assurance that these represent a good cross-section of the watershed-condition; (3) greater care in the securing of rainfall-data to be sure that the catch is truly representative in rate and in total; and (4) assurance that data on rainfall and runoff are properly synchronized.



The author believes that this type of derivation of infiltration-curves, though empirical, tends toward objectivity and elimination of the personal equation and further that such curves may be composited for a series of relatively homogeneous plots and single-cover watersheds, re-expanded to natural rainfall-conditions and used with a considerable degree of success in the estimating of surface-runoff from that particular portion of a larger watershed that is in the same general cover-complex. While the technique may seem on first trial to be laborious, it becomes less so with repetition and, furthermore, lends itself to routine that may be undertaken in large measure by technical assistants of sub-professional grade. The ultimate computation of surface-runoff under one set of conditions for a given storm, to volumes or depths for comparison with the results secured for another set of conditions, is the goal only partially attained.

The studies described in this paper were begun in 1943, while the author was engaged on hydrologic research work with the Soil Conservation Service. He is indebted to that Service for permission to complete this study on his own time, utilizing the Service's unpublished records. Especial acknowledgment is made to C. E. RAMSER, Research Specialist in Hydrology, LEWIS A. JONES, Chief of the Division of Drainage and Water Control, and M. L. NICHOLS, Chief of Research, Soil Conservation Service, who sanctioned the arrangement.

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American Geophysical Union,
Washington 15, D. C.

ADDENDUM--ADDITIONAL DISCUSSION

The following remarks regarding the paper on Hydrology of small watersheds under winter conditions of snow-cover and frozen soil by WALTER U. GARSTKA (see pp. 838-874) were received too late for inclusion with that paper.

J. E. CHURCH (Nevada Agricultural Experiment Station, Reno, Nevada)--WALTER GARSTKA'S progress-report is a welcome excursion to his runoff-project at East Lansing with opportunity to see his records in the making. The completeness of his equipment and his keen analysis of the phenomena give promise of accepted conclusions when essential data on individual problems have been accumulated. Unlike the Soda Springs Snow Project in the Sierra, the Michigan Project was deliberately located where the snow is shallow and freezing and thawing alternate throughout the winter. This will afford rare opportunity to study the effect of snow on soil.

In his field-measurements, the shallowness of the snow and the presence of wind during precipitation can be counteracted by combining many snow-samplings into one total and accumulating the cores in a bucket which can be carried to a place of shelter from the wind for weighing. The wind-movement associated with drifting and melting, estimated from the 90-foot wind-tower during the snow-melt of February 26, is now measured locally by a Soil Conservation anemometer 25 feet above soil-surface.

The present season has yielded rich suggestions, particularly the superabundant heat from solar and sky radiation above that required to melt the snow. The physics and rates of snow-melting have become dominant studies in snow.

WALTER U. GARSTKA (author's closure)--With reference to R. W. GERDEL'S comment on the density of the snow-pack at the time it contributes water to runoff, it was observed at East Lansing that at the bottom of the snow-layer the zone of saturation of the interstices of a snow-bank actively contributing to runoff was characterized by having a very shallow capillary fringe of water immediately above it. This capillary fringe did not appear to extend for more than one-half inch above the zone of saturation of a "ripe" snow. When in the "ripe" condition the snow at East Lansing had lost all semblance to the freshly fallen snow flakes. It consisted of ice-crystals at times approaching a size equivalent to half a grain of rice. Since a snow-layer can be thought of as a "soil" which tends to disappear at temperatures above 32°F, it is evident that the water-retentive capacity (against the action of the force of gravity) of the snow-"soil" will depend upon the texture, range of sizes, and arrangement of the snow- and ice-crystals. When the snow-layer is of large solid water-crystals, which are capable of exerting relatively small capillary forces, it is difficult to collect a sample of snow which can be said to be at the exact point of yielding, under field-conditions, free water. Precise technique for such determinations have not been developed as yet, to the writer's knowledge.

With regard to WALTER T. WILSON'S comment, it is admitted that the disturbing factors which he enumerated and those listed in the presentation operate to impair the validity of an exact comparison of precipitation-gage snow-fall records with snow-surveys. The basic hydrologic measurement is that of precipitation. In view of the fact that almost without exception the only winter precipitation-data published and used are those based upon standard non-shielded rain-gages, it was considered worth while to attempt the comparison. I understand that, within the last few years, the Hydrometeorological Division of the United States Weather Bureau has been engaged in the installation of a comprehensive network of shielded gages. One of these gages, with an ALTER shield, is being operated by the United States Weather Bureau at East Lansing, Michigan.

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